MiniCLEAN: Context, Status And Plans

Michael Ronquest

P-23 Weak Interactions Team (LANL)

For the CLEAN Collaboration

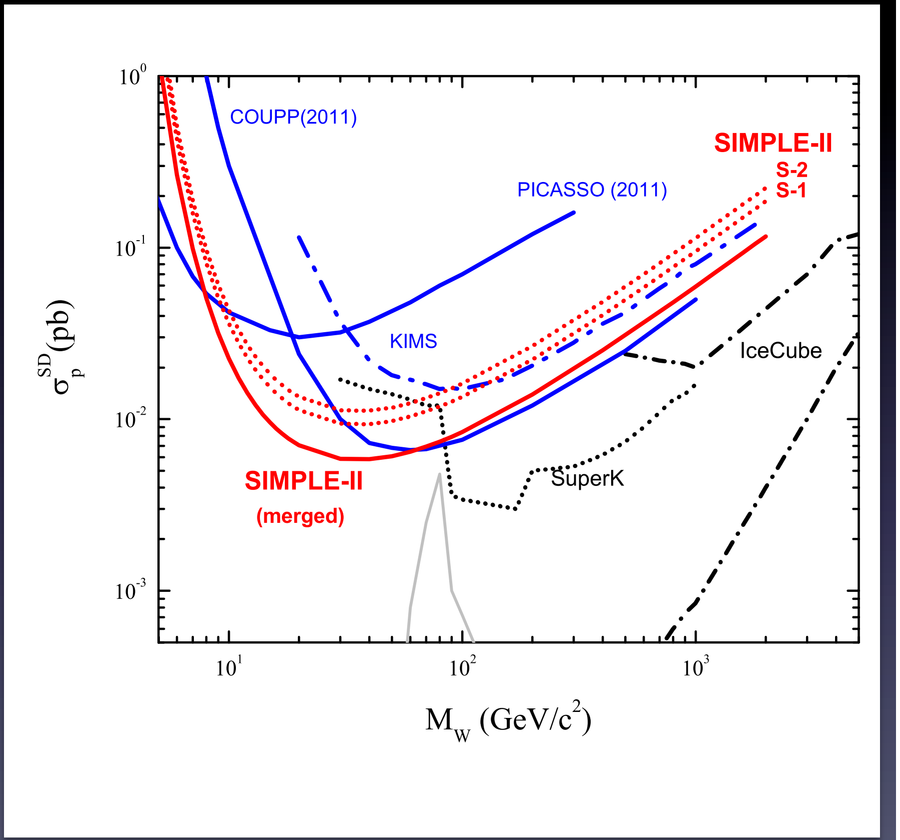
LA-UR-13-26673

Outline

- Survey Of Direct Searches
  - Direct Search Strategies
  - Discrimination Techniques
  - Survey of (some) current and near-term planned experiments
- MiniCLEAN Design and Status
  - Relation to DEAP-3600
  - The MiniCLEAN Detector
  - Contrasts With DEAP-3600
  - Run Plan And Deliverables
  - Future Prospects

Survey of Direct Detection

- Exciting time for direct WIMP searches
  - New technologies starting to mature
    - Noble Liquids
    - Superheated liquids
    - Solid state detectors
  - Technologies with "interesting" results soon to be tested
    - NaI
    - HPGe
- Direct searches are starting to cut deeply into MSSM phase space



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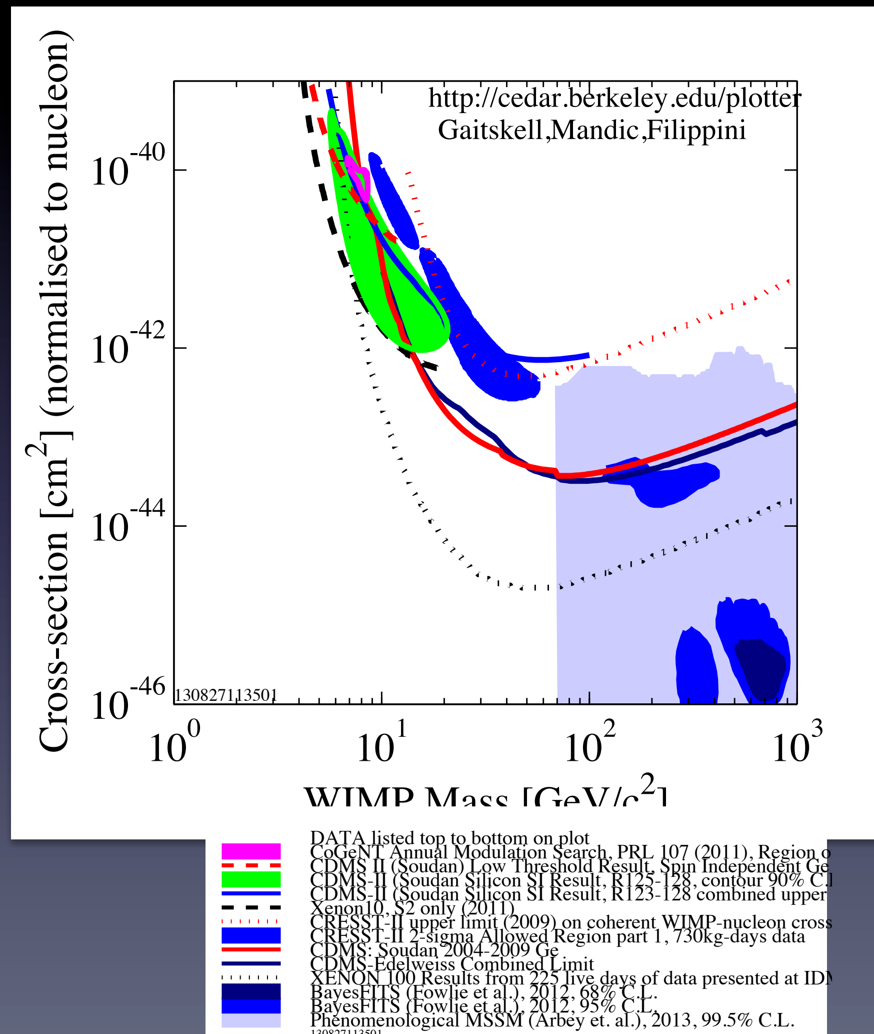

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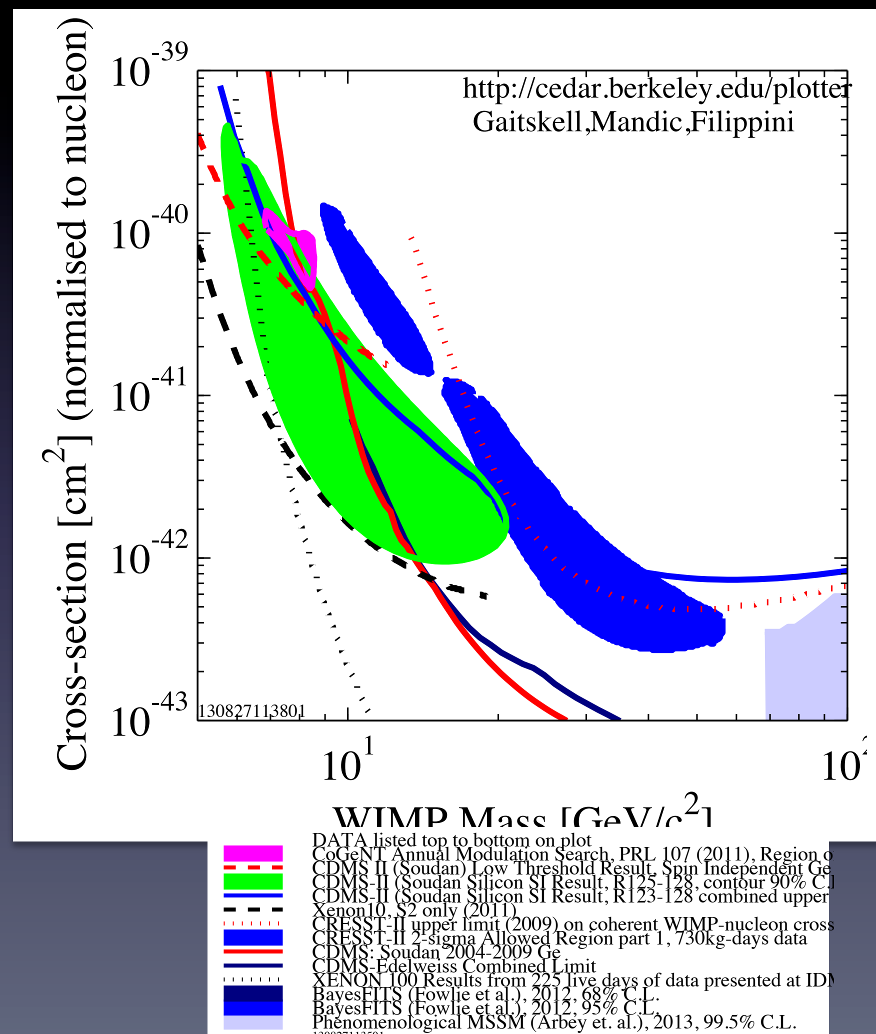
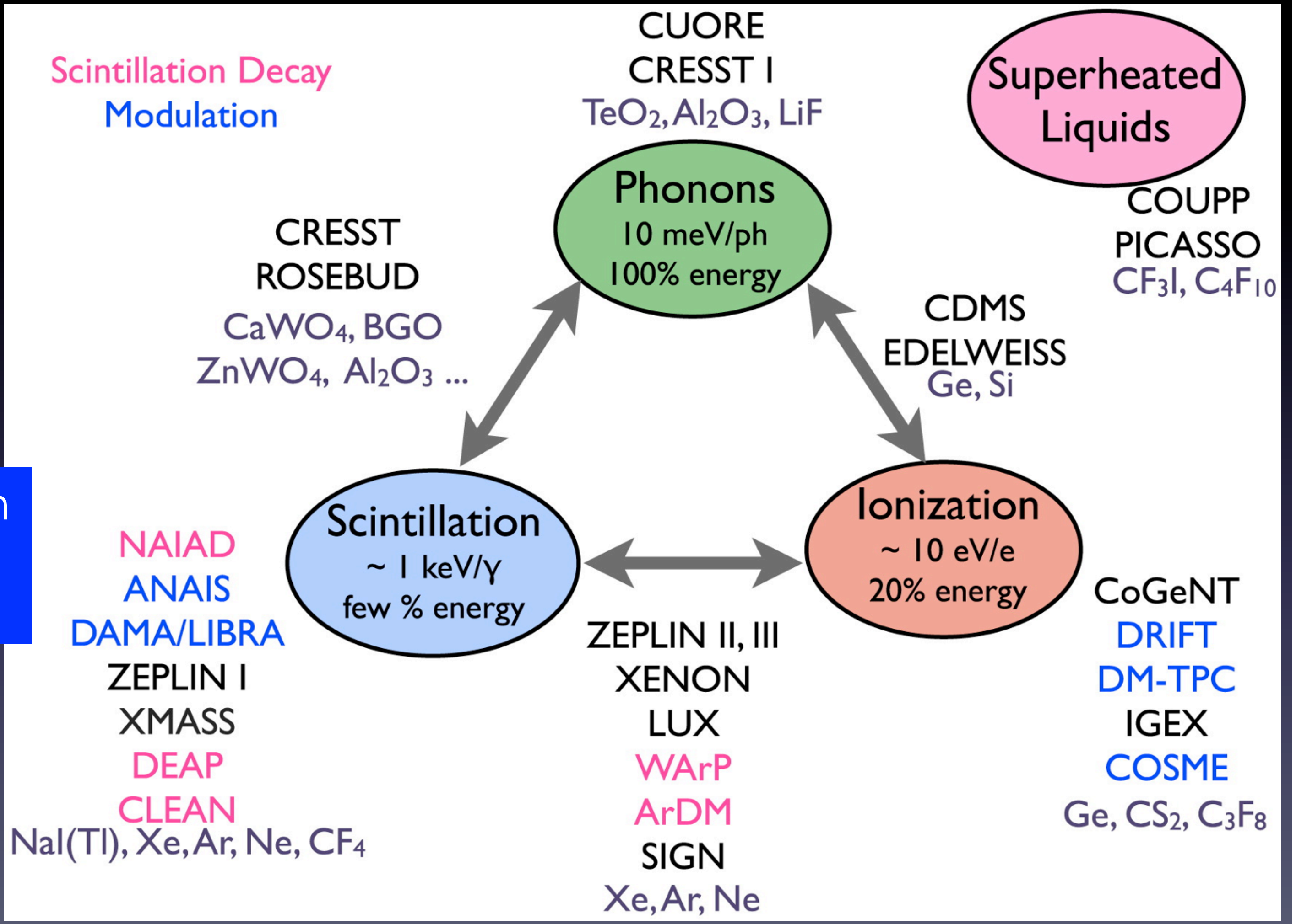


Direct Search Strategies

- WIMP interactions are rare:
  - Detector should have low backgrounds
  - And a large mass
- WIMP interactions expected to produce low energy O(10keV) recoils:
  - Want low energy thresholds
- These recoils are nuclear recoils
  - Want ability to identify nuclear recoils vs electronic recoils
- For spin-independent WIMP-nucleon interactions: want high A target
- For spin-dependent WIMP-nucleon interactions: want high J target,
  - protons or neutrons are unpaired

- Underground and in heavy shielding
- Efficient detection schemes
  - Charge
  - Light
  - Heat(photons)
- Desire discrimination ability
- Careful choice of elements or compounds:
  - S.I.: Xe,W
  - S.D.: F, I

Discrimination

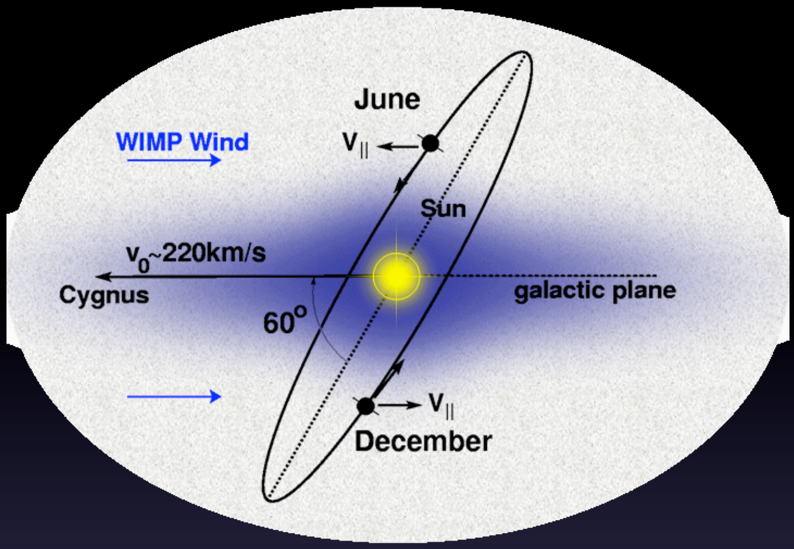


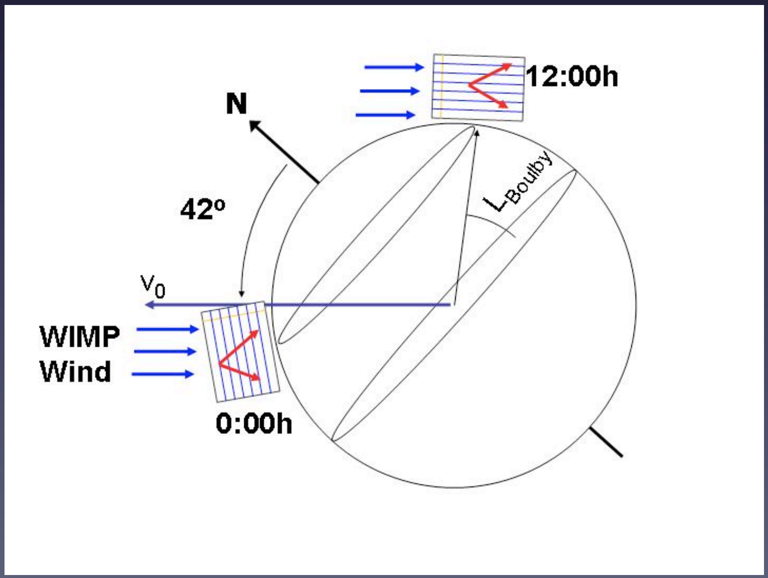
Discrimination often breaks down at low energies

[E. Figueroa-Feliciano]

"Lab Frame" effects

- Expect interaction rate to vary due to relative velocity of Earth in relation to apparent "WIMP wind"
  - Requires very stable experiment in order to see small effect
  - Strong correlation with seasonal variations though
- "WIMP wind" comes from direction of Cygnus
  - A directional signal would be exceptionally hard to fake
  - See Dinesh Lomba's talk next

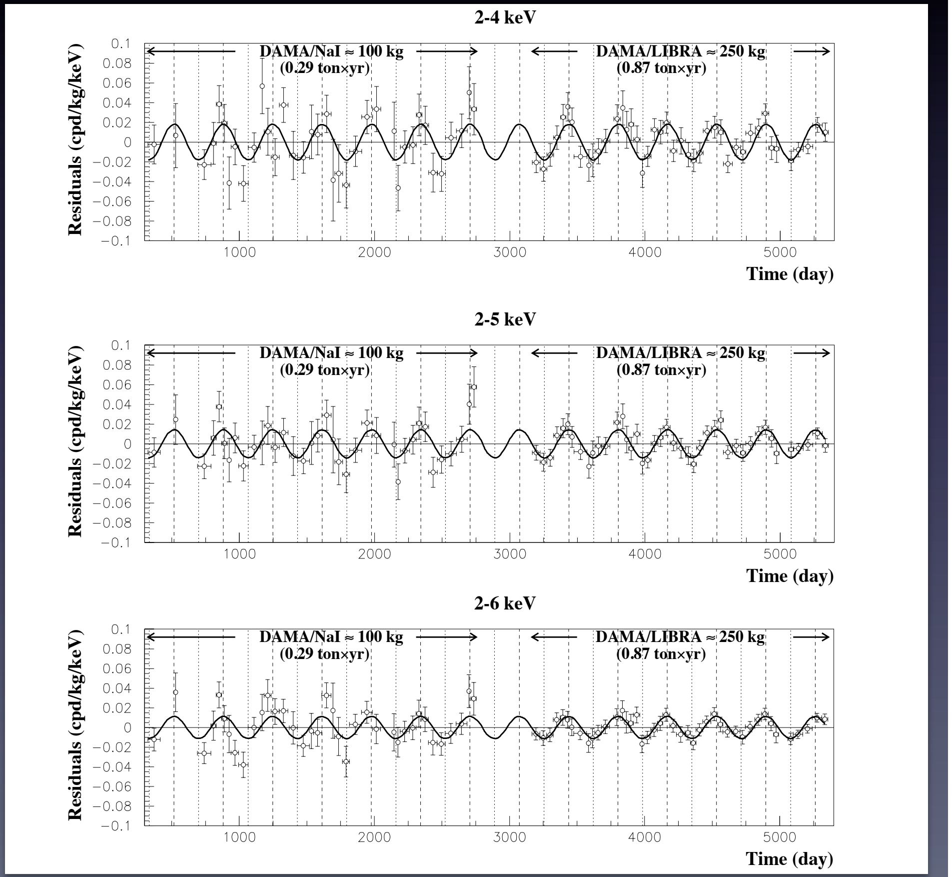




U Sheffield

DAMA/LIBRA

- Long term program built around ultra- low background NaI(Tl) developed in conjunction with Saint-Gobain
- Beautiful, and shocking variation in count rate @ 2-6keV over many years
- But, <u>no discrimination</u>, and results are in tension with many other experiments using different technology
- This is either a very non-standard WIMP, or a very interesting background
- Number of collaborations are attempting to confirm DAMA/LIBRA with their own NaI(Tl) experiments……

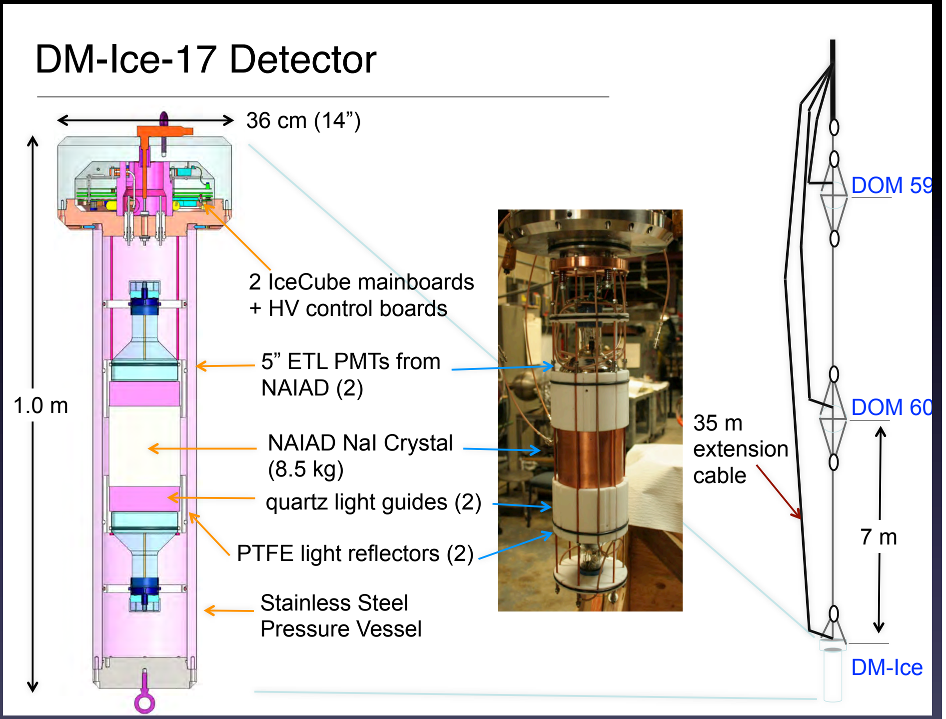


"Dark Matter investigation by DAMA at Gran Sasso", Int. J. of Mod. Phys. A 28 (2013) 1330022

DM-ICE: DAMA revisited

also KIMS, NAIAD, ANAIS, Princeton…

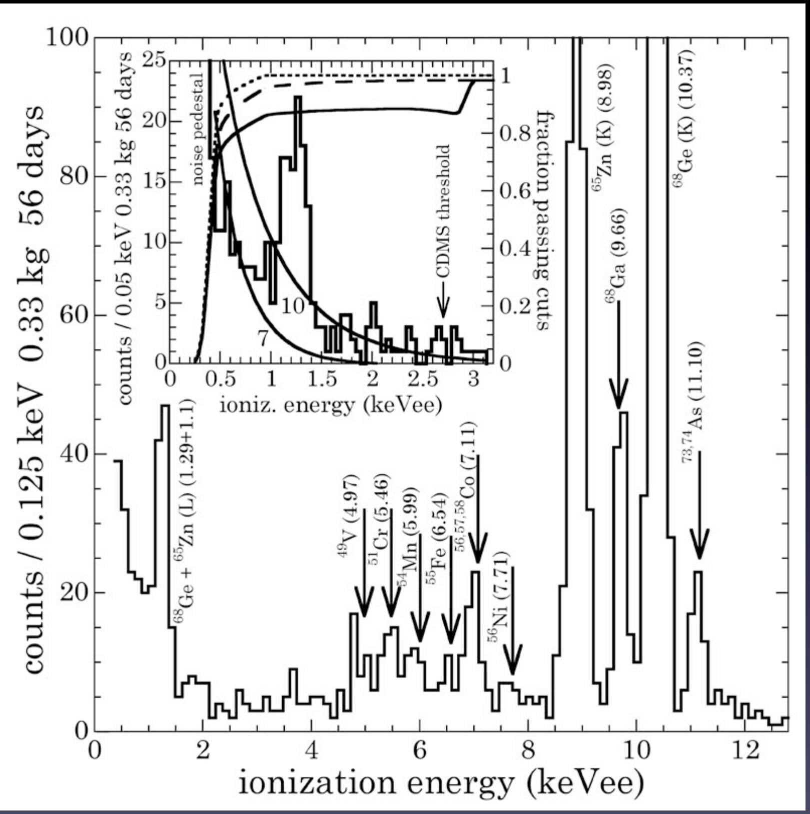
- Key problem: obtaining radiopure NaI(Tl) crystals
- Second problem: DAMA signal could be related to season somehow
- Radical Solution:
  - Re-develop ULB NaI(Tl)
  - Flip any seasonal effect and head south….all the way
- Location in Ice Cube:
  - Good overburden, good moderator, and very radiopure
  - Conditions are a challenge……
- With enough crystals (~250kg +) would be only way to truly confirm DAMA signal is astrophysical in origin



Reina Maruyama

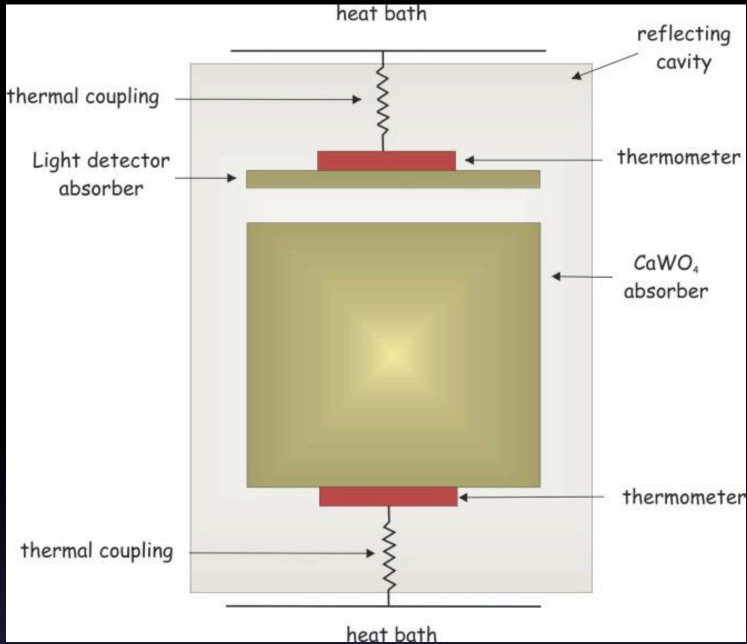
CoGeNT

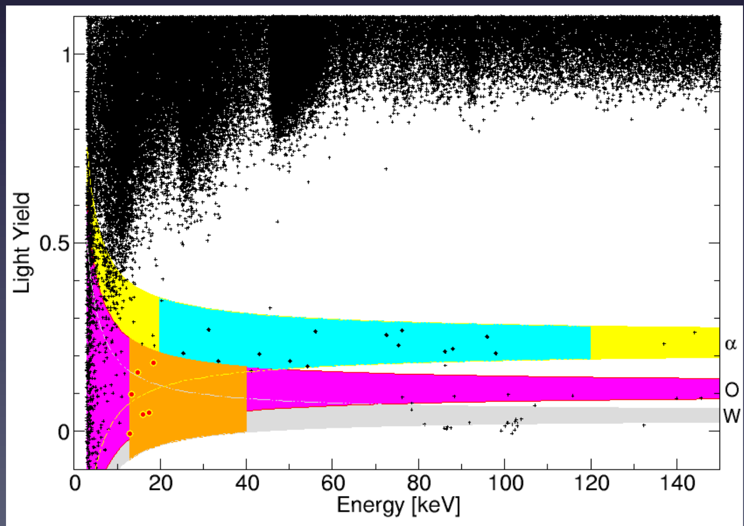
- Point-contact HPGe: charge collection only
- Evidence of unexplained counts below 1 keV
- Also evidence of annual variation of count rate…
- Tension with other results
- Data from Majorana Demonstrator will be quite interesting…….



CRESST II

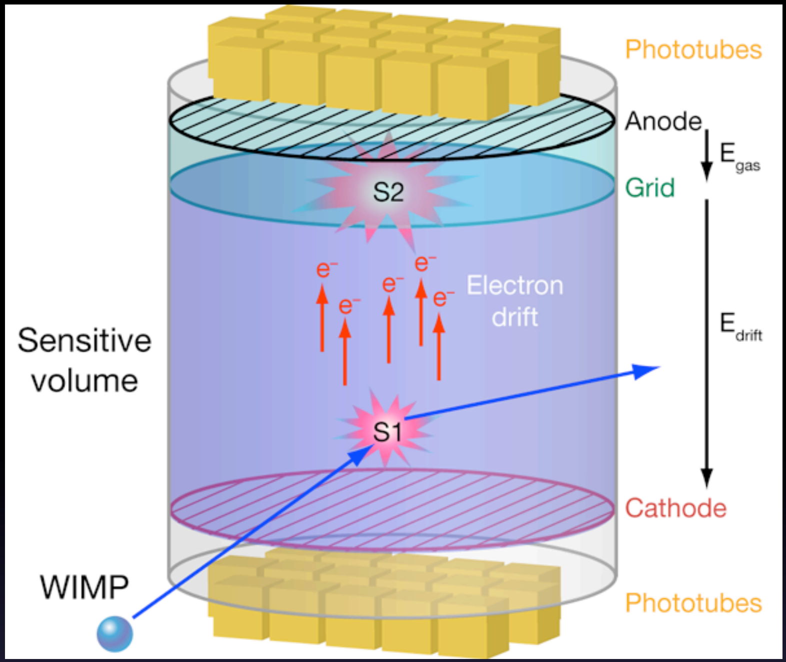
- $CaWO_4$ target with heat/scintillation light readout
- Partial ability to separate target elements
- See excess of events in acceptance region [Eur. Phys. J. C (2012) 72:1971]
- But: "In the light of this result it seems unlikely that the backgrounds which have been considered can explain the data, and an additional source of events is indicated. Dark Matter particles, in the form of coherently scattering WIMPs, would be a source with suitable properties. We note, however, that the background contributions are still relatively large. A reduction of the overall background level will reduce remaining uncertainties in modeling these backgrounds and is planned for the next run of CRESST"
- Main issue: alpha backgrounds (see Kuzniak et el. (arXiv1203.1576))
- New run started Spring 2013



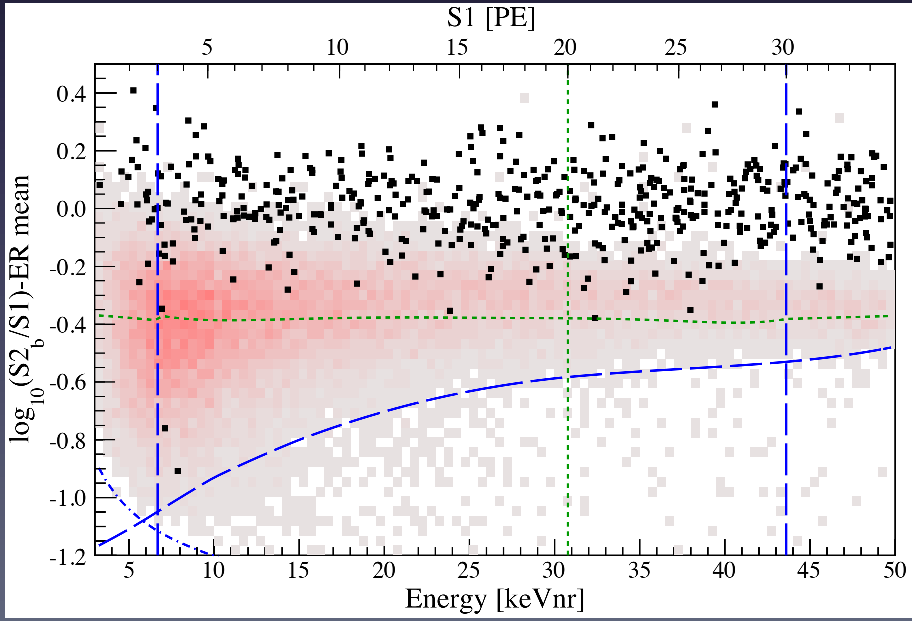


XENON100

- LXe: good charge mobility and scintillation yield
- Current leader with peak sensitivity of $\sigma_{SI} < 2 \times 10^{-45}$ cm^2 at 55 GeV/c^2 [arXiv:1207.5988]
- Exclusion of CoGeNT, DAMA,CREST-II @ > 90%
- Primary questions relate to L_{eff} near threshold



Alan Stonebraker



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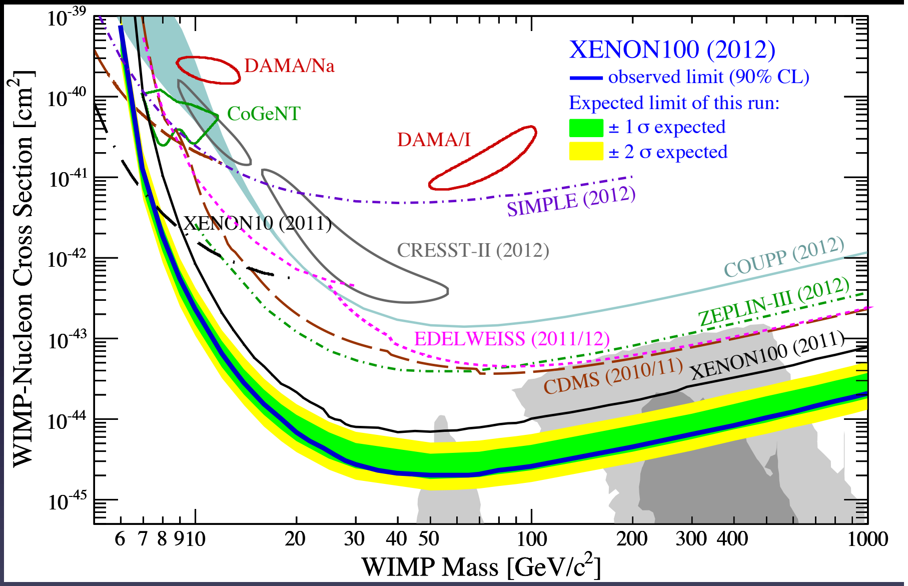

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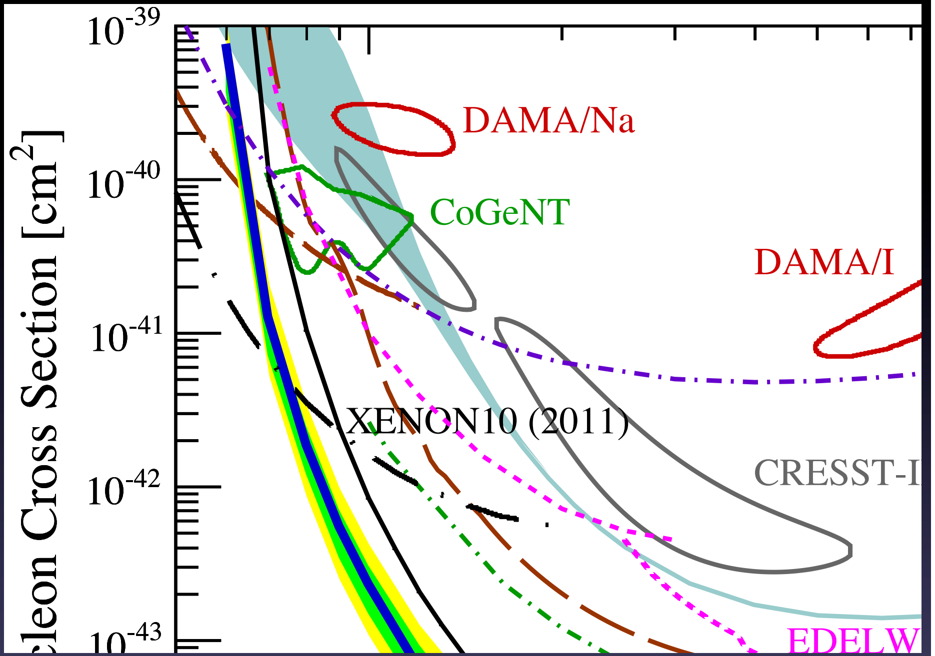
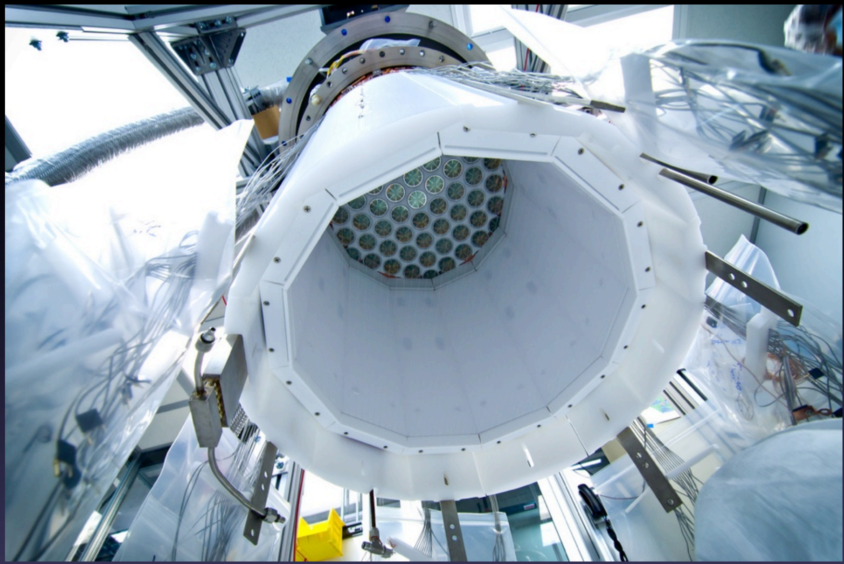
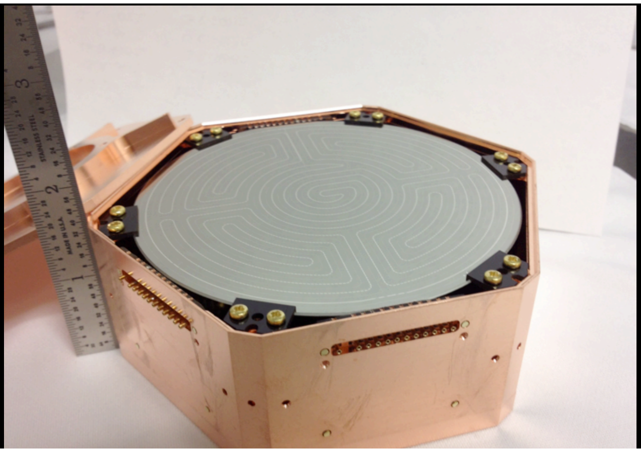


LUX/Xenon 1T

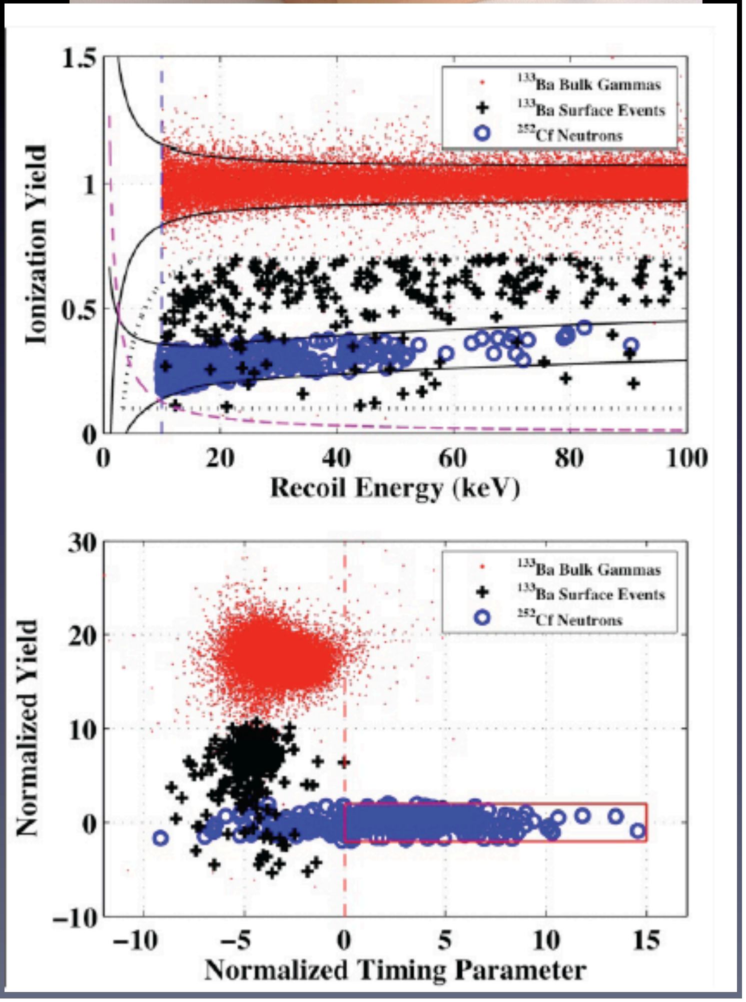
- LUX running now!
- Similar design, larger fiducial volume (34kg vs 100kg) than XENON100
- Expect lower threshold
  - Concerns regarding L_{eff} become more pronounced
- Expect result by end of calendar year, sensitivity projected to be $\sigma_{SI} < 2 \times 10^{-46}$ cm^2
- Xenon 1T (fully funded and under construction) projects a sensitivity of $\sigma_{SI} < 2 \times 10^{-47}$ cm^2



CDMS



- Simultaneous readout of phonons and ionization
- Long steady improvement of readout technology to improve recoil discrimination and surface event rejection
- Cost and scaling are still issues
- Search with Ge not in tension with CoGeNT
- New results with Si: three candidates:
  - Still partial tension with XENON100



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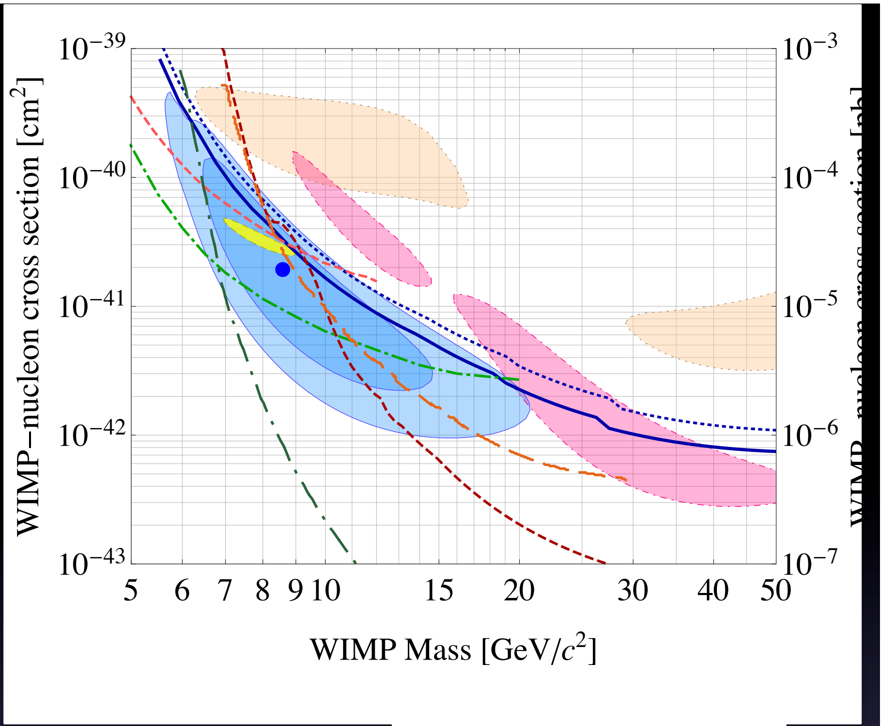
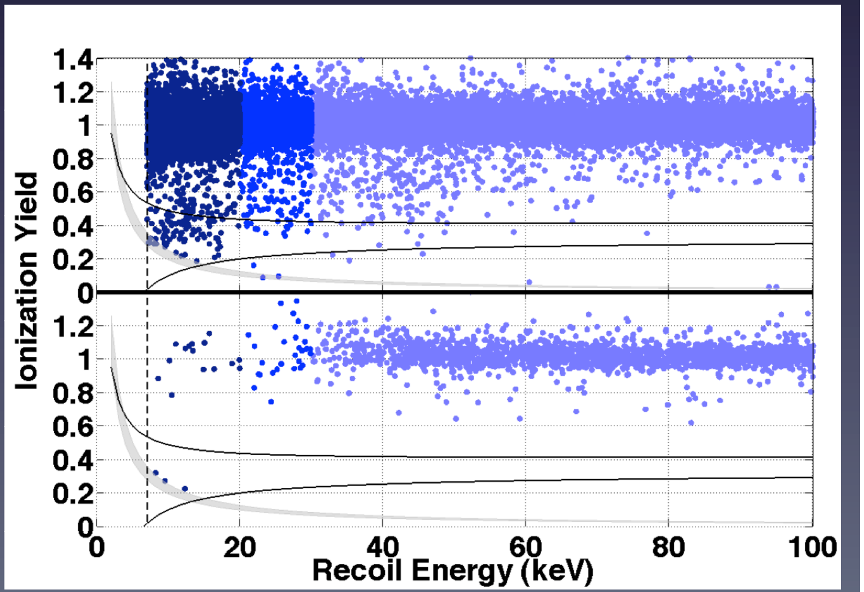


arXiv:1304.4279



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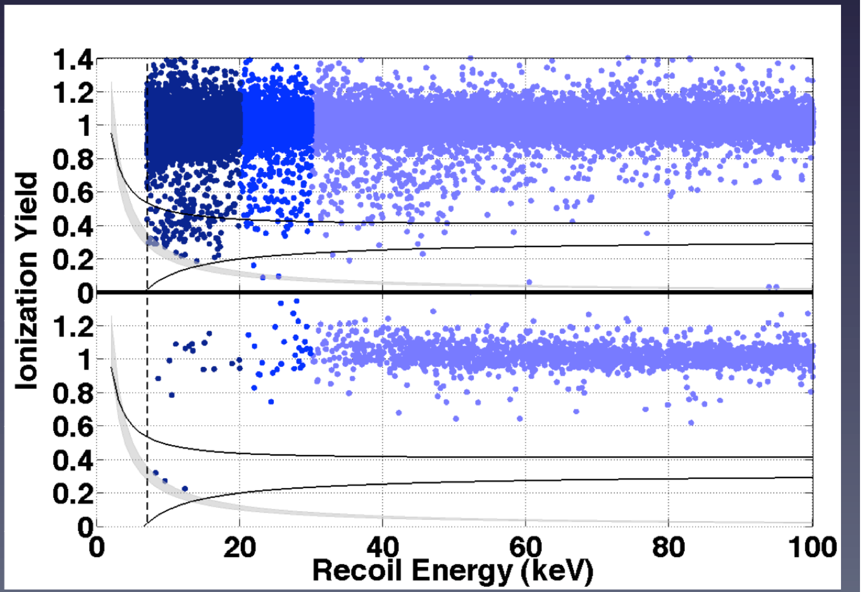
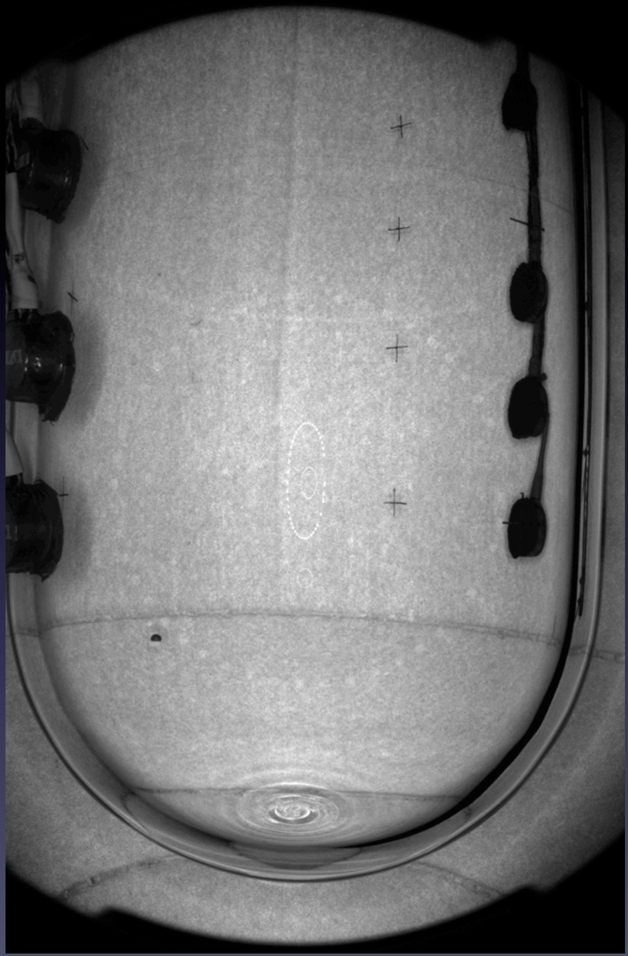
"Though this result favors a WIMP interpretation over the known-background-only hypothesis, we do not believe this result rises to the level of a discovery."

arXiv:1304.4279



COUPP

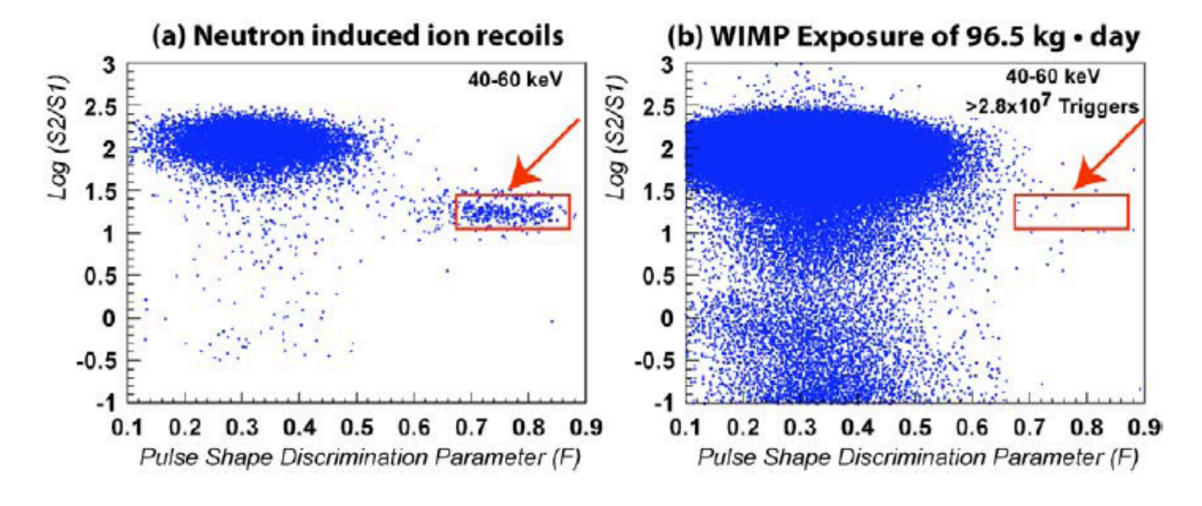
- Bubble chamber: set P and T so that γ, β do not create bubbles
  - Alphas still a background, but reject using PICASSO's acoustic rejection technique: these events are louder at high frequencies than nuclear recoils
- COUPP-60 now running with 40kg of CF_3I
  - Eventually 2 year run up to 80kg
- COUPP-4 2.6kg of C_3F_8 "soon"
  - Lower threshold, better spin-dependent sensitivity
- Good mix of Spin dependent and spin-independent sensitivity
- Great target exchange capability: explore SI and SD signals
- Threshold detector only: no energy information



DarkSide

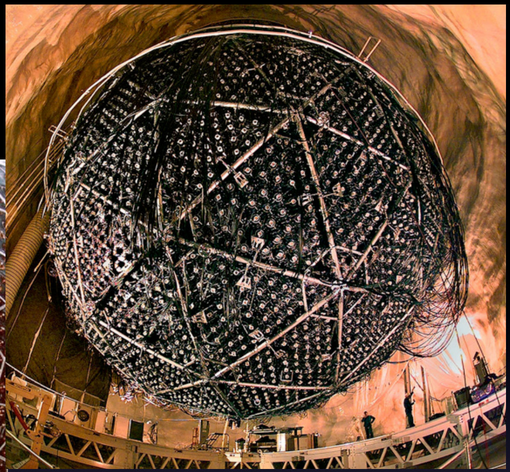
- Dual-phase LAr:
  - S2/S1 rejection like Lxe
  - Also use PSD from S1
- Follow-on to WArP, adds
  - Depleted Argon target
  - High QE PMTs + other optical upgrades
  - Liquid Scintillator Neutron Veto (actually Borexino CTF)
- About to commission 50kg detector
- 3 year exposure → $\sigma_{SI} < 2 \times 10^{-45}$ cm^2 sensitivity projected

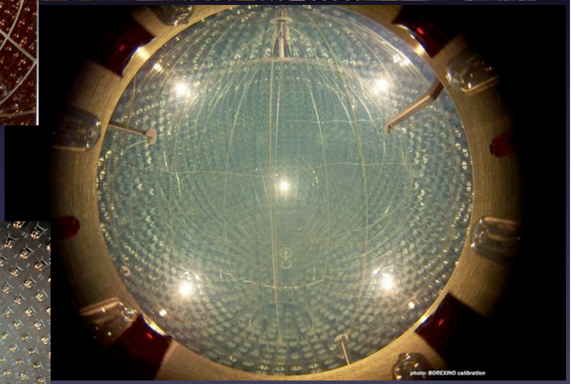
Astropart.Phys.28:495-507,2008

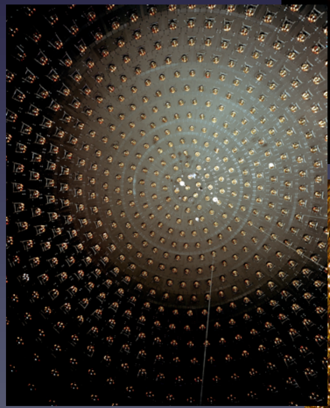


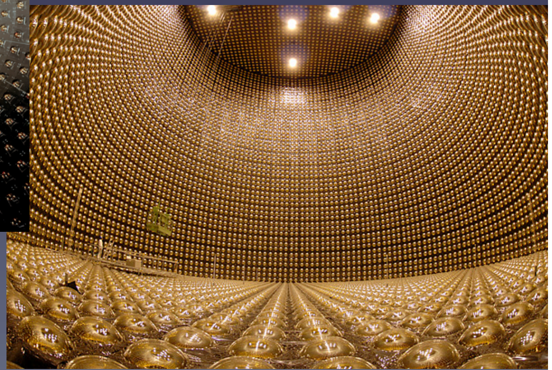
Single-phase detectors

- Recent history of "Large and Simple" monolithic ν detectors being successful
- Simple = Scalable
- Simple = Easy to understand and operate
- Single-phase monolithic WIMP experiments seek to replicate this: "just a large, clean detector filled with scintillator"
- DEAP, CLEAN and XMASS are the single-phase WIMP experiments









Dual phase vs single phase

Single phase

- Trigger windows can be fast: < 5 microseconds
  - High rate calibration runs are possible
  - Independent of detector size
  - Pile-up from ^{39}Ar less of a concern
- No messing with drift fields
  - Simpler detector
  - Looser purity requirements , which can be monitored with triplet lifetime
  - Easier to scale to large sizes, like SNO, KamLand, etc…
- With proper thermal insulation/ cooling, LNe is an option

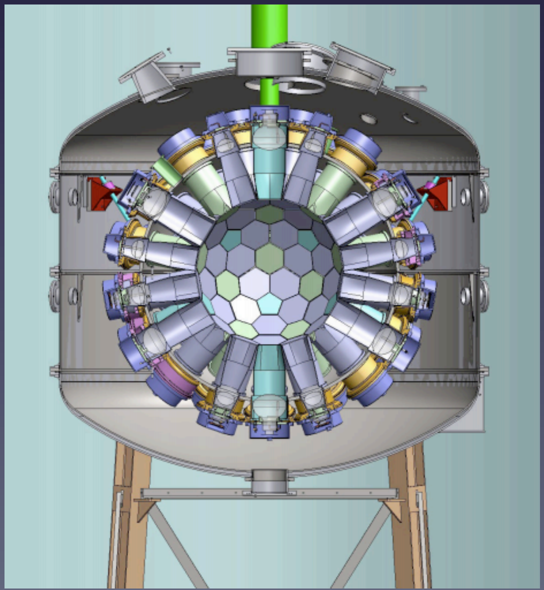
Dual Phase

- Collection of ionization charge provides second channel for recoil discrimination
  - Lose light so weaken electron recoil rejection
- TPC design permits detection of multiple elastic recoils
  - Or use external neutron veto
- TPC also rejects surface alphas
- Requires Depleted Argon due to drift times

DEAP and CLEAN

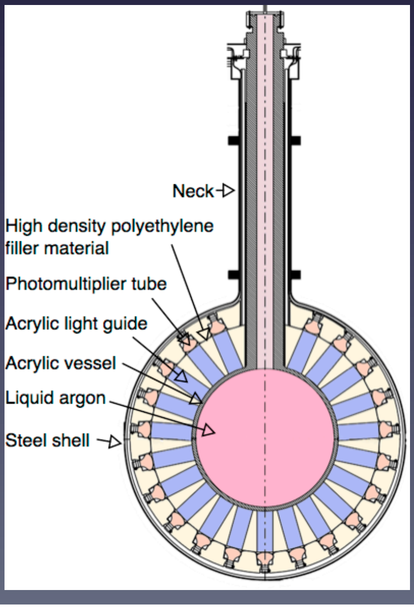
MiniCLEAN

- 500kg total of LAr, held in steel cryostat, observed by "cold" PMTs



DEAP-3600

- 3600kg of LAr, held in acrylic vessel, observed by "warm" PMTs



DEAP and CLEAN

MiniCLEAN

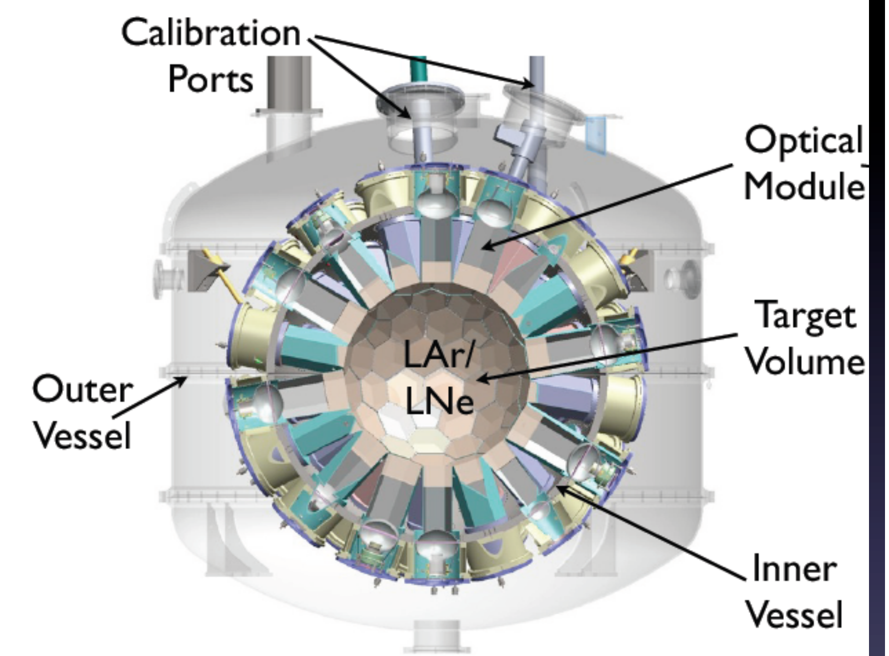
- Primarily focused on the use of LAr for dark matter searches
- Key additional capability of running with LNe target:
  - Target swap --> test WIMP signal , backgrounds using same detector
  - Also useful for future neutrino experiments
- Focus on light yield and position reconstruction
- "Soccer ball" segmentation
- LAr fill in Dec 2013
- PSD Demonstration for DEAP-3600, G3 detectors

DEAP-3600

- Focused solely on LAr dark matter searches
  - Will use DAr
- Focus on passive suppression of neutron backgrounds
- "Golf ball" segmentation
- Cool-down around Jan 2014
- Sensitivity of 10^{-46}

MiniCLEAN Goals

- With our optical design:
  - Measurement of light yield
  - Demonstration of 3D position reconstruction
- At our light yield:
  - High statistics measurement of the background PDF due to PSD leakage of 39Ar decays
    - → Limit of PSD in argon
  - Informs future target choices in large argon detectors
- With our detector:
  - Measure backgrounds (surface alphas, neutrons, etc)
  - Test analysis and background rejection techniques
- For additional $ε :
  - A LNe experiment that informs future designs for DM, p-p solar neutrino and coherent neutrino scattering experiments



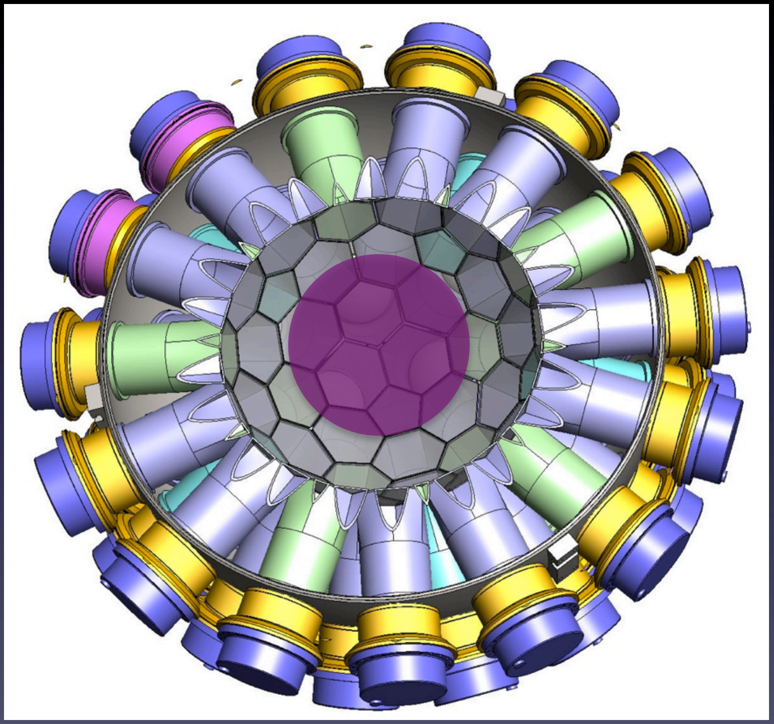
92 8” cryogenic PMTs
Wavelength shifter (TPB) @ R=43 cm
PMTs @ R=81 cm

MiniCLEAN's LAr Target

- Liquid argon is an excellent choice for detection
  - Material is cheap : $2k/ton
  - Bright scintillator: output equivalent to NaI(Tl)
  - Purification is straightforward:
    - Hot getters
    - Cold carbon
  - Dense enough to offer some self shielding
    - $\rho \sim 1.4$x water
  - Atomic physics results in miraculous difference in scintillation between electronic recoils and nuclear recoils
    - Electron recoil leakage $< 4.7 \times 10^{-8}$ for 25keVee < E < 86keVee [M.G. Boulay, et al. arXiv:0904.2930] → rejection of gamma, beta radiation demonstrated
    - Electron recoil leakage of 10^{-10} or better projected
- Challenges:
  - 1Bq/kg ^{39}Ar beta decay background present in atmospheric argon
    - Results in a very useful "always –on " calibration source
  - Cryogenics @ 87K
  - Vacuum UV scintillation light @120nm → direct optics really, really hard

MiniCLEAN's LAr Target

- Liquid argon target:
  - Four regions of interest:
    - Central fiducial volume (selected using position reconstruction) ~ 150 kg
    - Active volume: 500kg, outer portion serves as active veto
    - Lightguides: partially active (more on this later)
    - Interstitial spaces between lightguides: completely passive (more on this later)
  - Total amount of argon: 3400 kg



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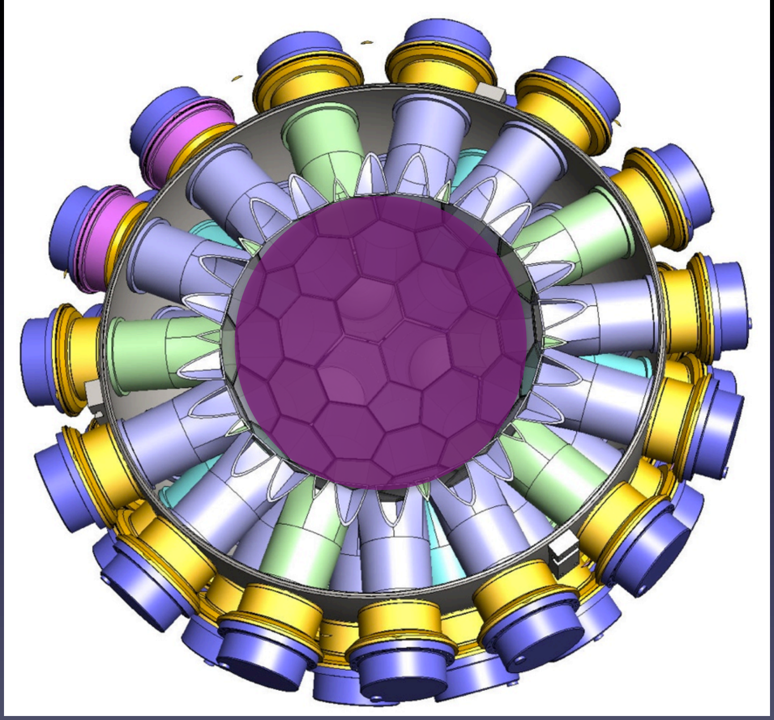

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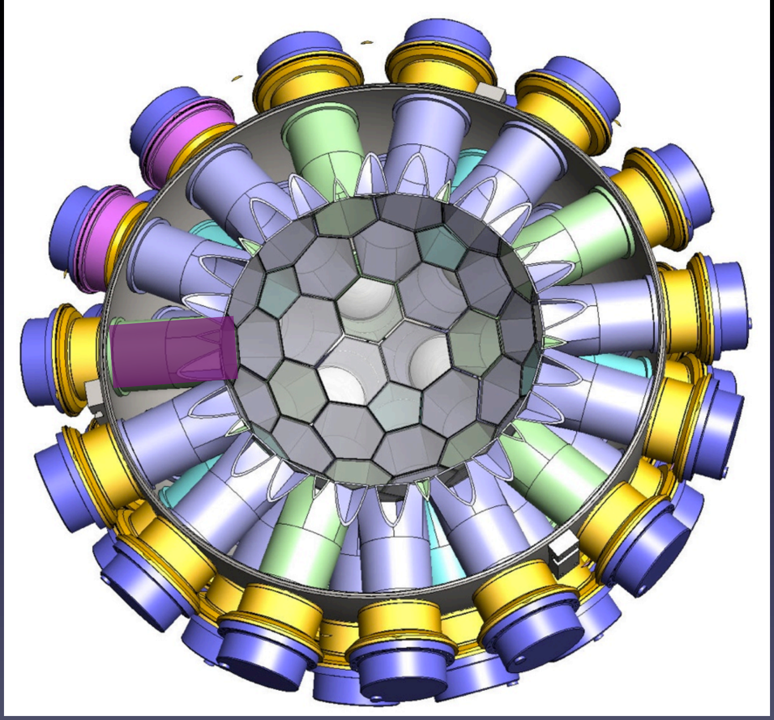

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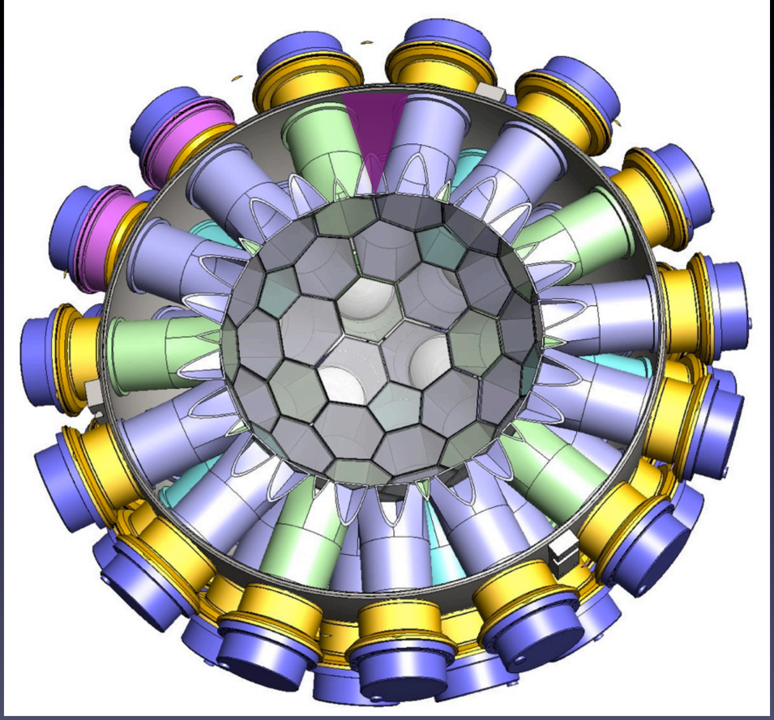
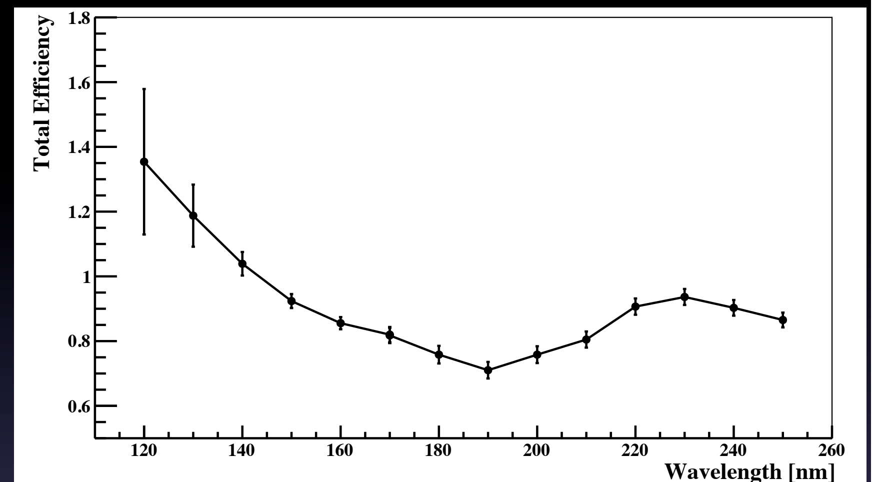
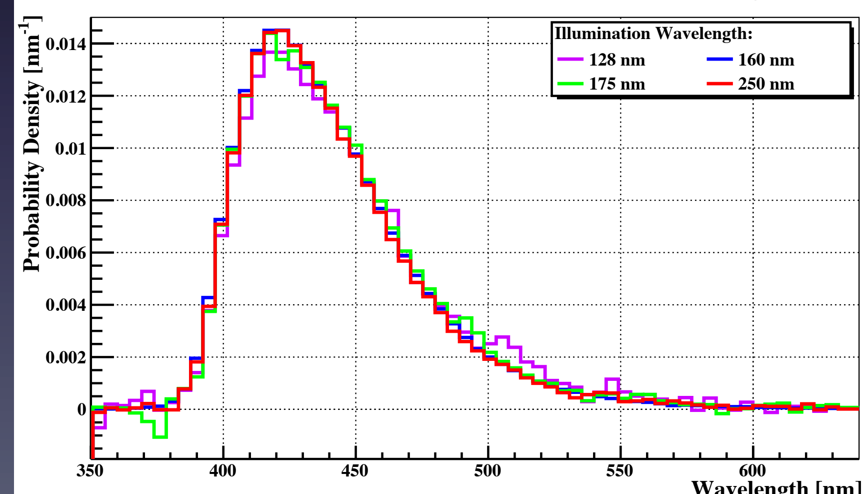


MiniCLEAN: Wavelength Shifter

- VUV scintillation light must be shifted into visible for detection by photomultipliers
- We use tetraphenyl butadiene (TPB) for its wavelength shifting efficiency:
  - Over 100% efficient at shifting 120 nm VUV scintillation photons to ~ 430nm (indigo) photons
- Vacuum deposited
- TPB is also a (weak) scintillator, so surface alpha emitters are a concern

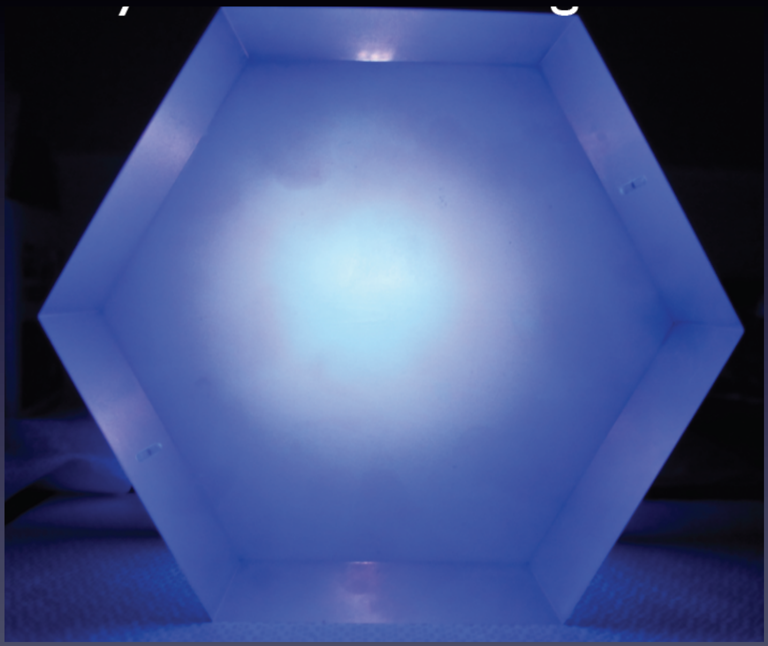




NIM A, 654, 1, 2011, Pages 116-121

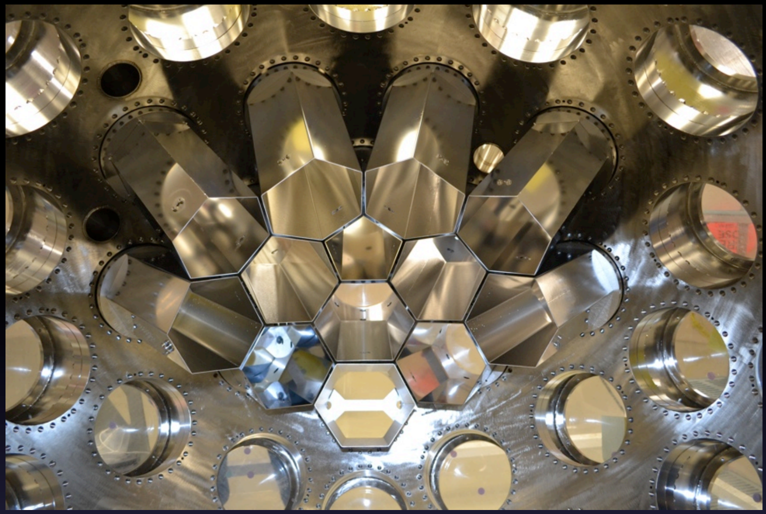
MiniCLEAN: acrylic blocks

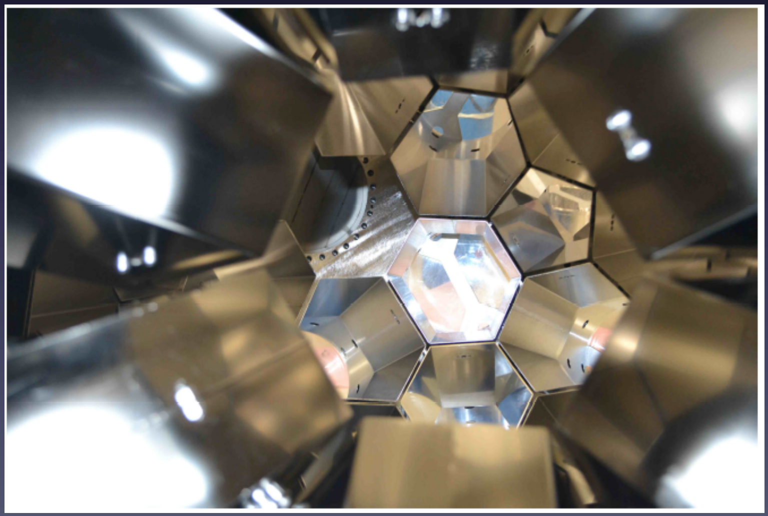
- Acrylic blocks terminate the inner portion of the lightguides
  - Provide surface for TPB deposition
  - Moderate of neutrons
  - Thickness set by need to balance light transmission with neutron background



MiniCLEAN: Lightguides

- Steel lightguides in three different polygonal shapes to define a 92 faced polyhedron
  - Maximizes active (photocathode) surface area
  - Nearly 100% pixelization → minimize reflections in active region
  - Better position reconstruction
- Filled with argon for neutron shielding
- Lined with 3M Vikuiti ESR reflective coating
  - Minimizes reflective loses from TPB layer to PMTs
  - Known known to be a (poor) wavelength shifter [Optical Reflectance Measurements for Commonly Used Reflectors, Janecek, Moses, IEEE TNS 09/2008] → makes light guides partly active (~10%) and analysis more challenging
  - Same material as "baffles"…





MiniCLEAN: Lightguides

- Scintillation light from interstitial spaces between lightguides may leak into central volume
  - Our “crack problem”
- Produces reconstructed events low in energy and with unpredictable reconstructed position due to topology
  - Low photon statistics will increase odds of PSD leakage
  - First seen during gamma calibration studies, produces low energy tail
  - Seen again in very early neutron background studies: increased background due to reconstruction, energy leakage
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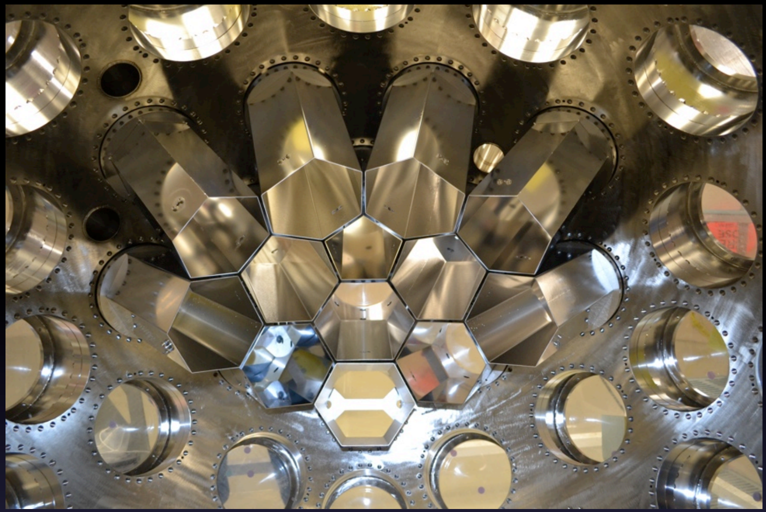
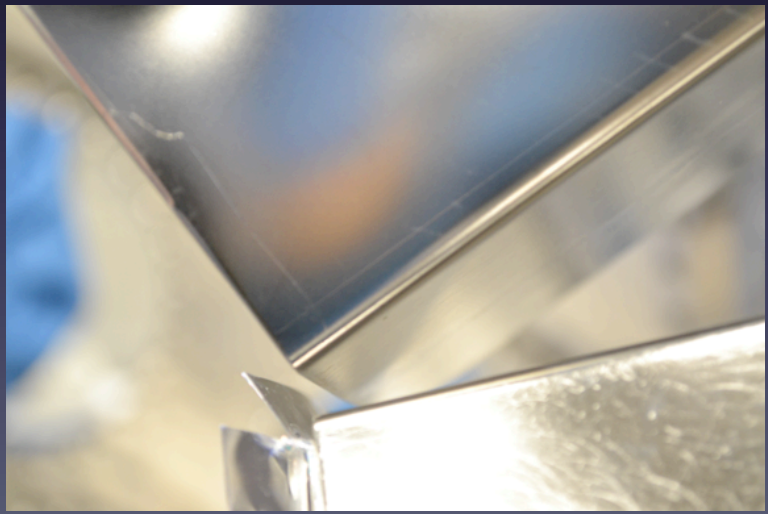
- Will block light with “baffles” extending from each side of polygonal light guide





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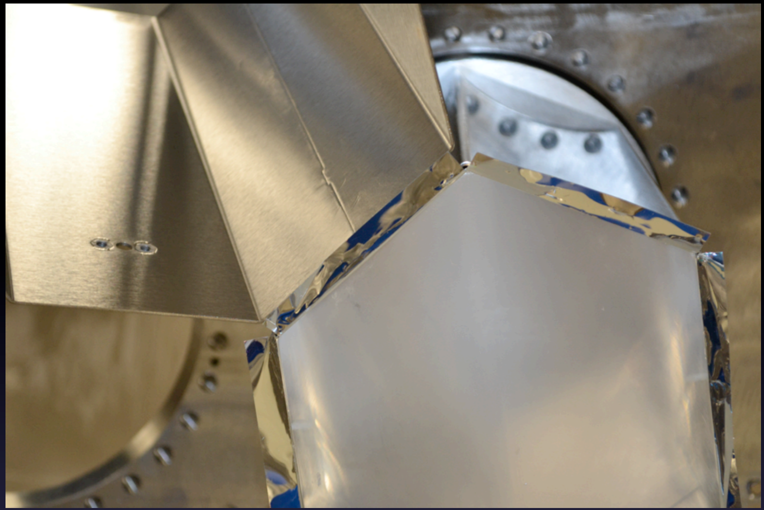

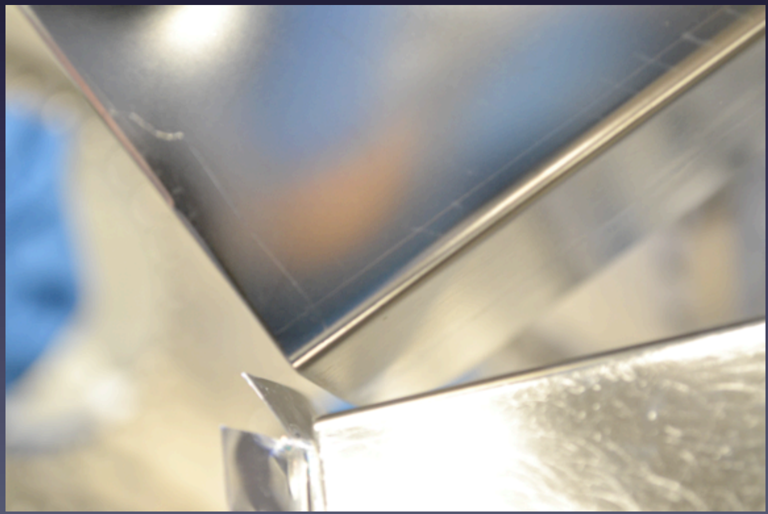

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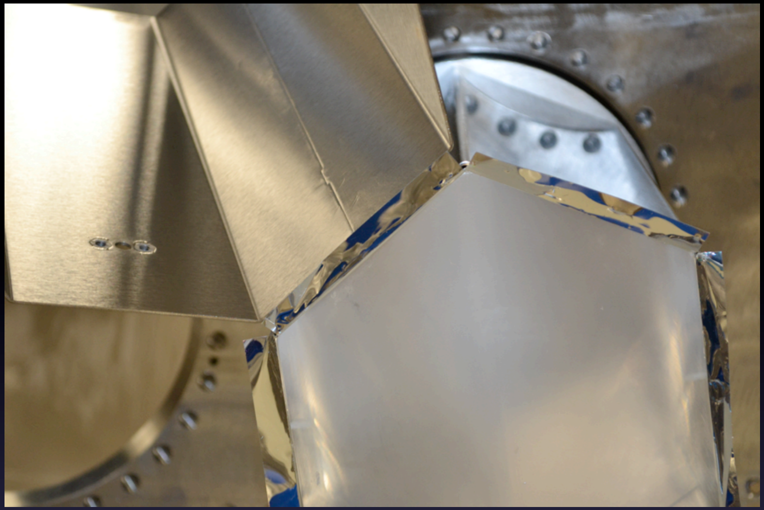
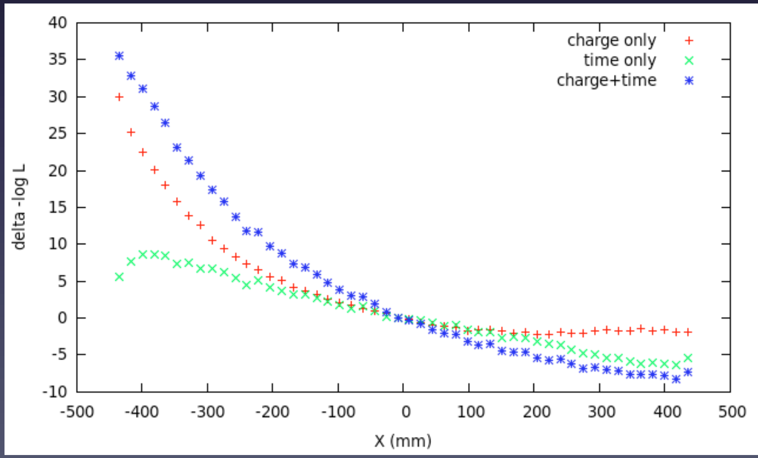
- Will block light with "baffles" extending from each side of polygonal light guide
- Also developing timing based cut to further reject "crack " and surface events



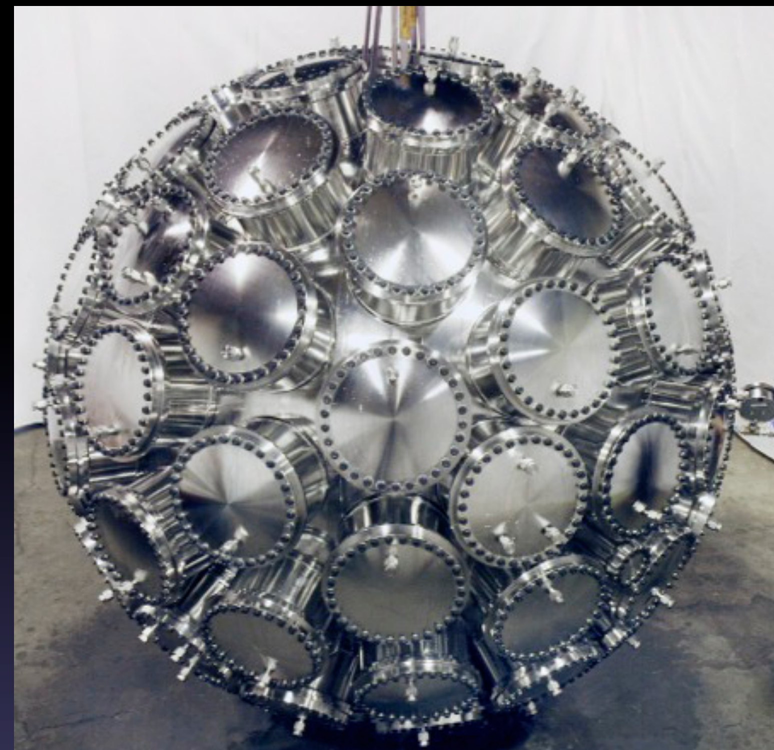


MiniCLEAN:PMTs

- Cold r5912-02MOD PMTs: direct immersion in argon improves light collection at the price of reduced efficiency:
  - Q.E.(T)
  - Platinum underlay to improve charge mobility
  - (α,n) reactions from U/Th contamination in these borosilicate tubes generate the dominant neutron background in MiniCLEAN

MiniCLEAN: Inner Vessel

- Beautiful piece of engineering:
  - ASME Code Stamped Pressure Vessel
  - Precision machining to assure proper nesting of the front of the polygonal lightguides
  - Made of Outokumpu 316L SS
    - Not recycled
    - Assayed to be low-background steel



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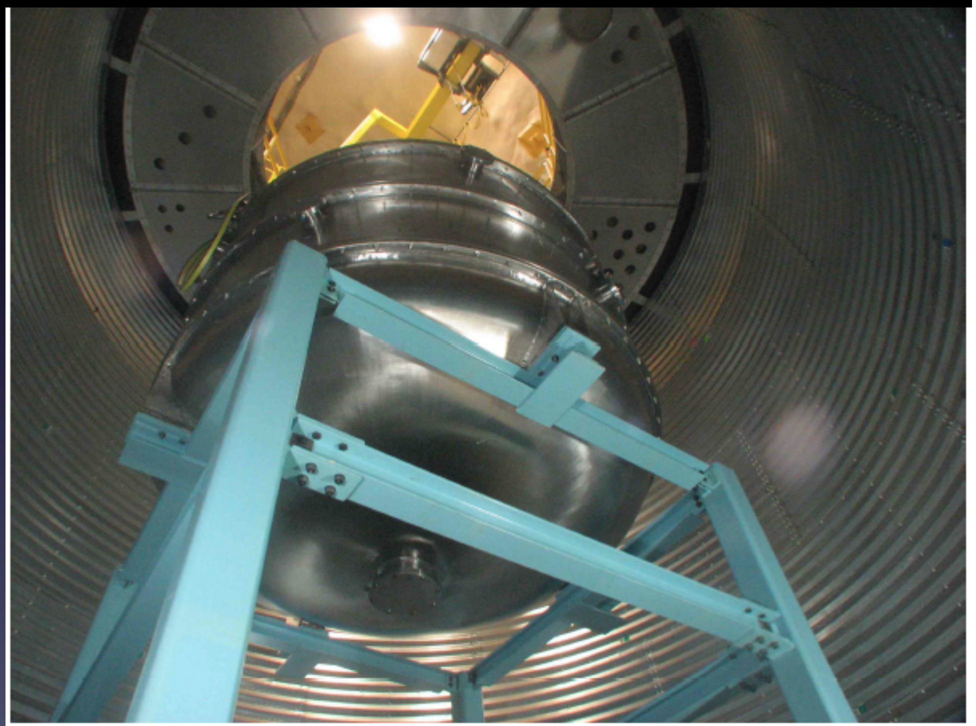
MiniCLEAN: Outer Vessel and Water Shield

- IV suspended inside evacuated outer vessel (OV)
- OV located inside large water shield
  - Shields against cavern neutrons
  - Also cavern gammas (for LNe)
  - Instrumented as a cosmic ray veto
  - Magnetic compensation coils on outside → improves efficiency of some PMTs
- Location: SNOLAB @ 6800 feet



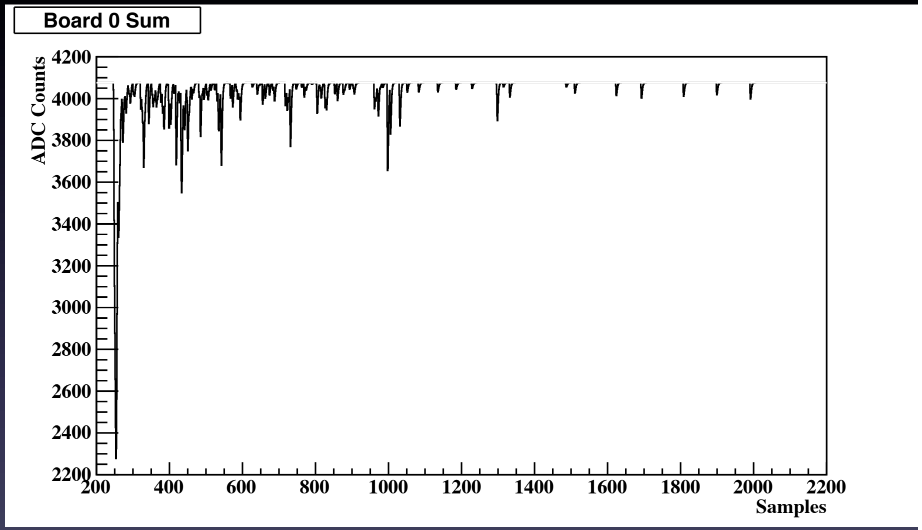
Event Reconstruction

- Events are reconstructed in a phase space of
  - Reconstructed Energy
  - Reconstructed Position
  - A PSD observable which labels the event as a nuclear recoil, electron recoil or "something else"

- Recall MiniCLEAN's goals:
  - Measurement of light yield
  - Demonstration of 3D position reconstruction
  - Determination of limit of LAr PSD

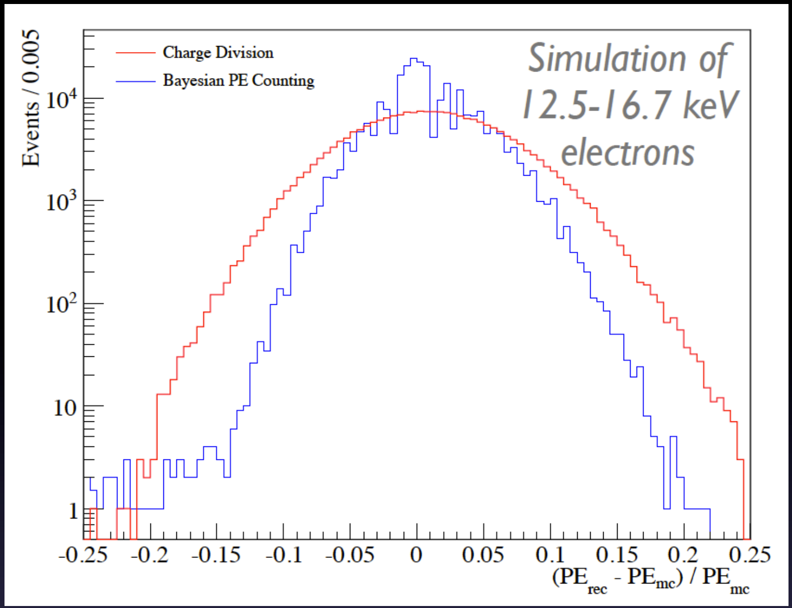
Event Reconstruction

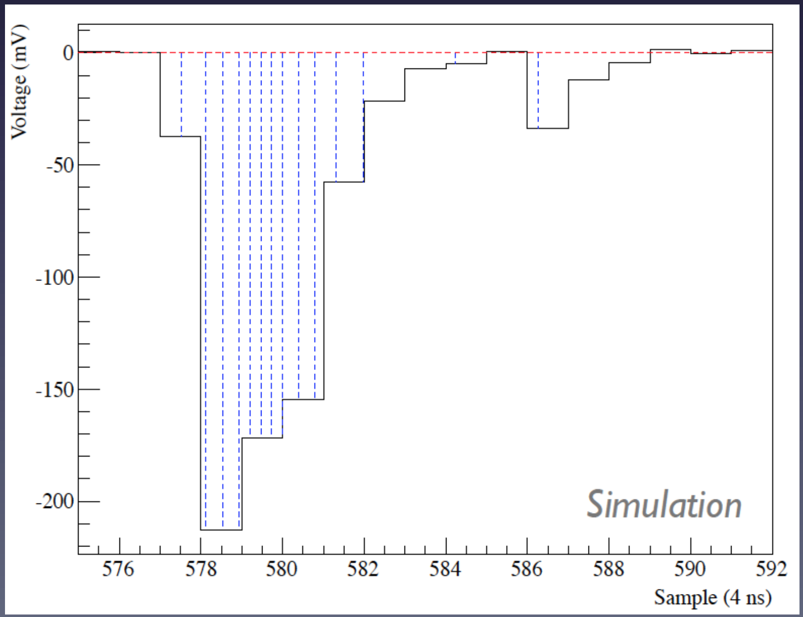
- Will fully digitize individual PMT waveforms
  - Required for Pulse Shape Discrimination
  - Permits counting of single photoelectrons
    - Permits rejection of noise and improves energy resolution, PSD and position reconstruction
  - PE calibration can be done continuously, per PMT in long triplet tail of scintillation pulse
    - Plenty of events thanks to ^{39}Ar



Bayesian Single PE counting

- Need to deal with PE pileup in prompt region
- Bayesian single PE algorithm → higher performance than simple charge division
- Determines # PE and time for each waveform
  - Improves energy resolution at low energies
  - Benchmark energy scale with ^{39}Ar





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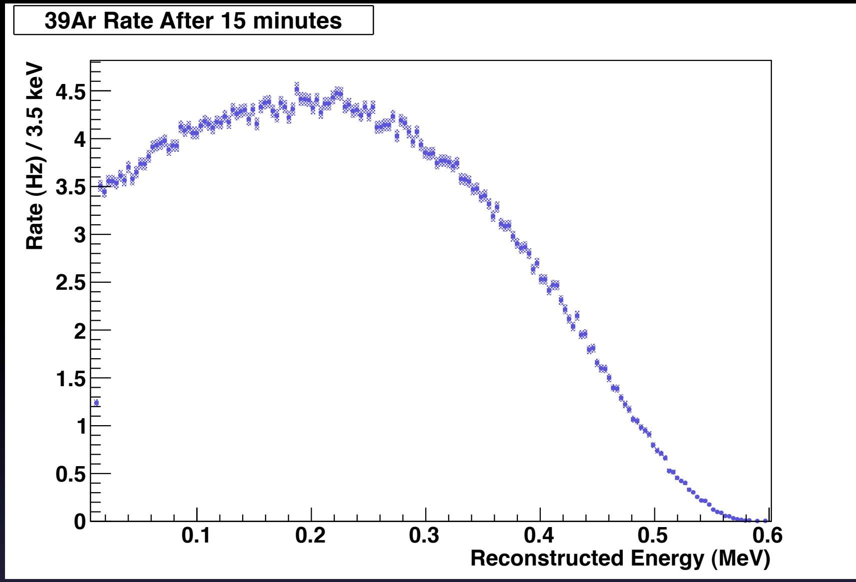
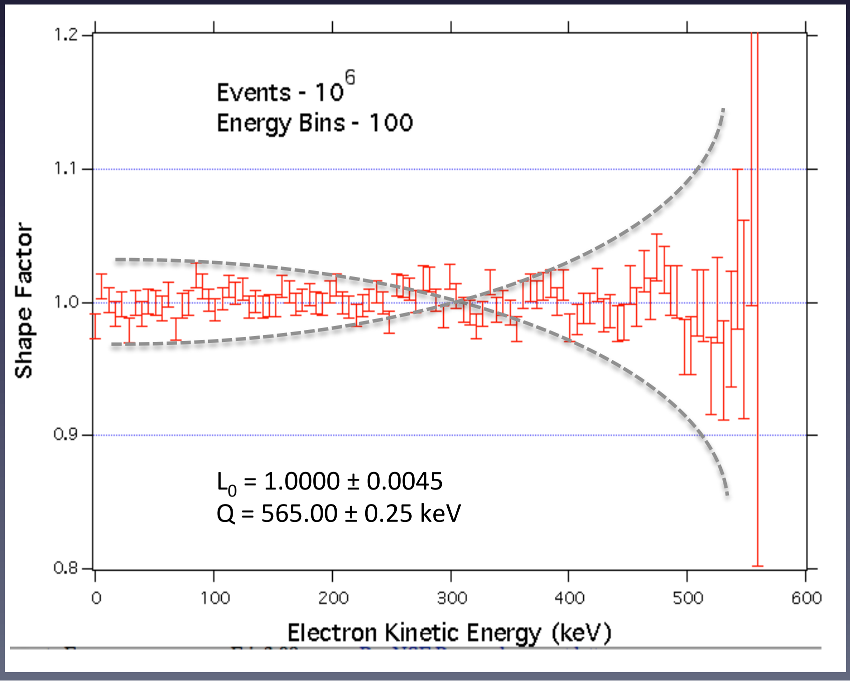
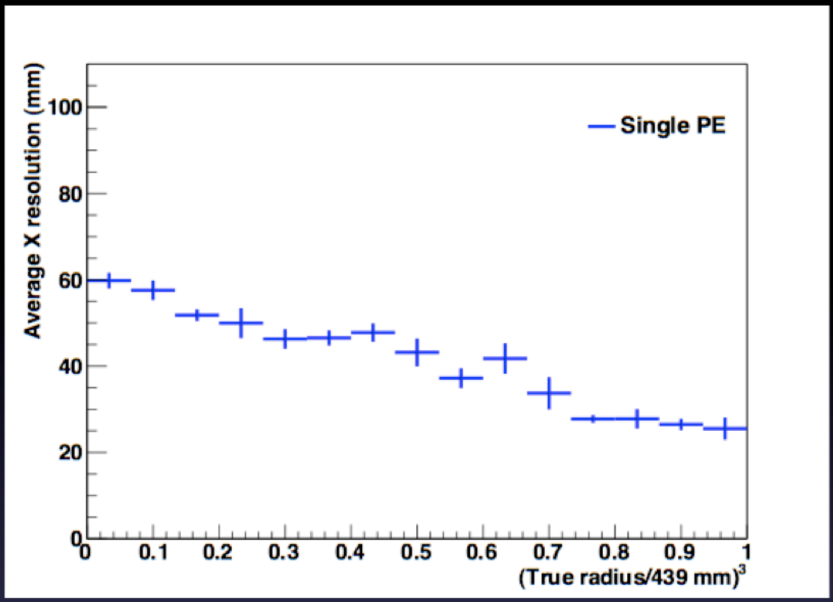
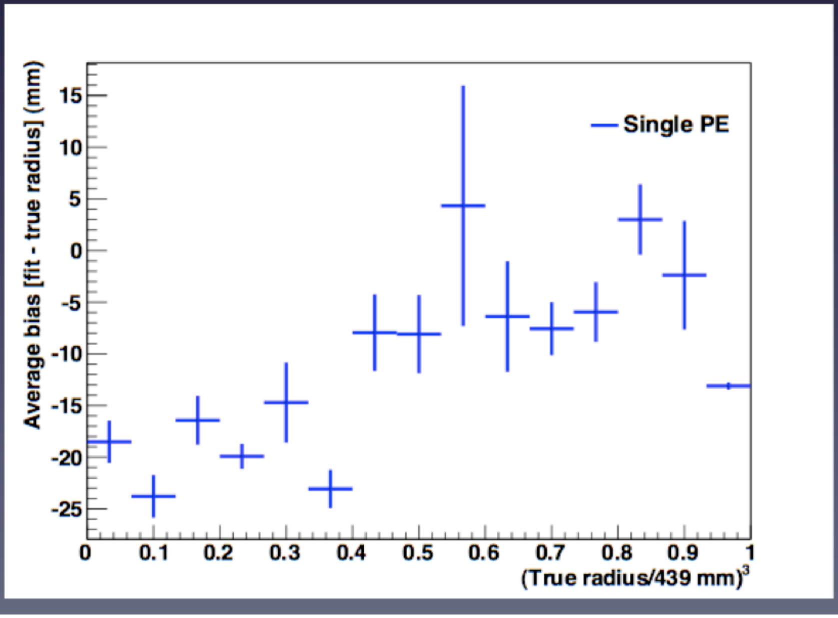




Position Reconstruction

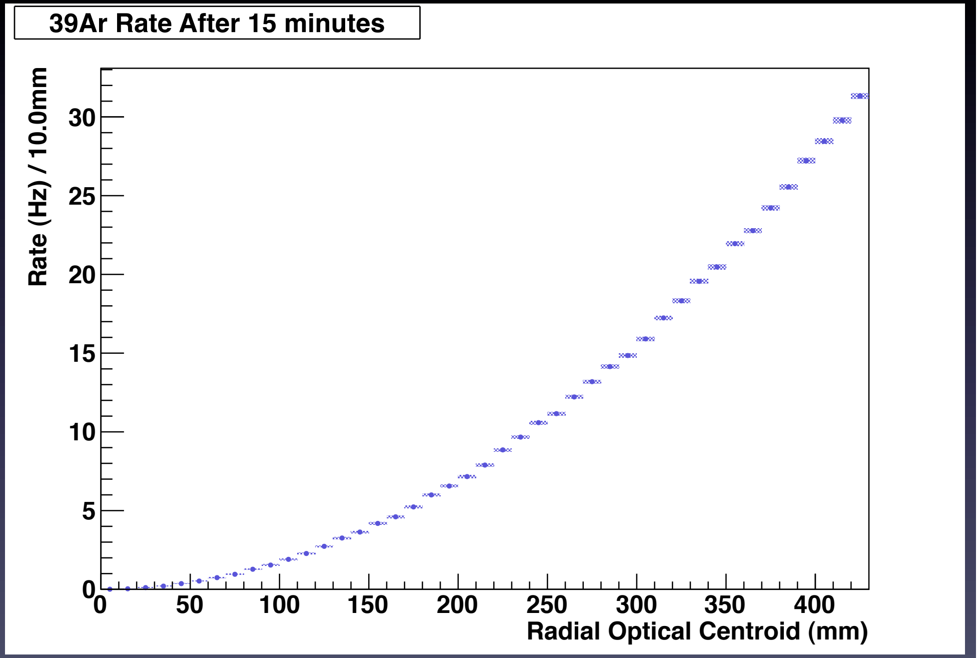
- Using likelihood based approach to predict location of each event
  - # PE hits in each tube (PE counter)
  - Recall that TPB re-emits visible light isotropically—no direct light
  - UV and visible optical models from MC coded into likelihood
- Benchmark with data….





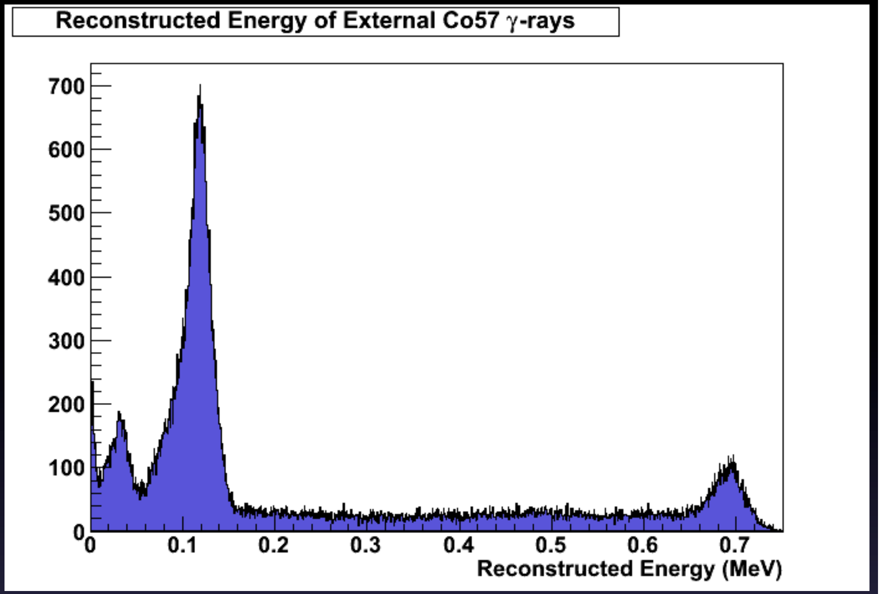
Position Reconstruction

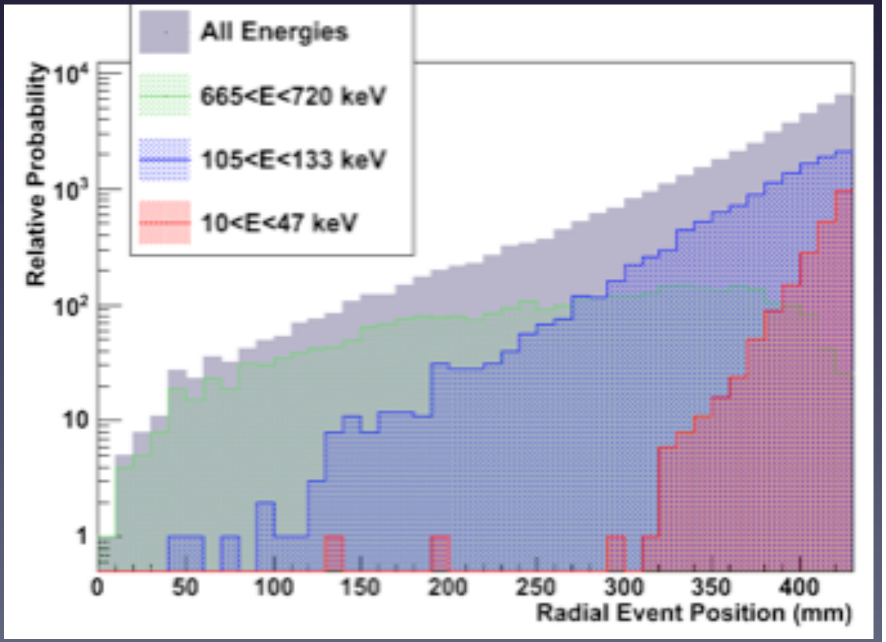
- Position resolution, bias studied using multiple distributions:
  - Uniform ^{39}Ar decays
    - <u>Differential</u> rate goes as r^2
    - Energy band: threshold – 565keV



Position Reconstruction

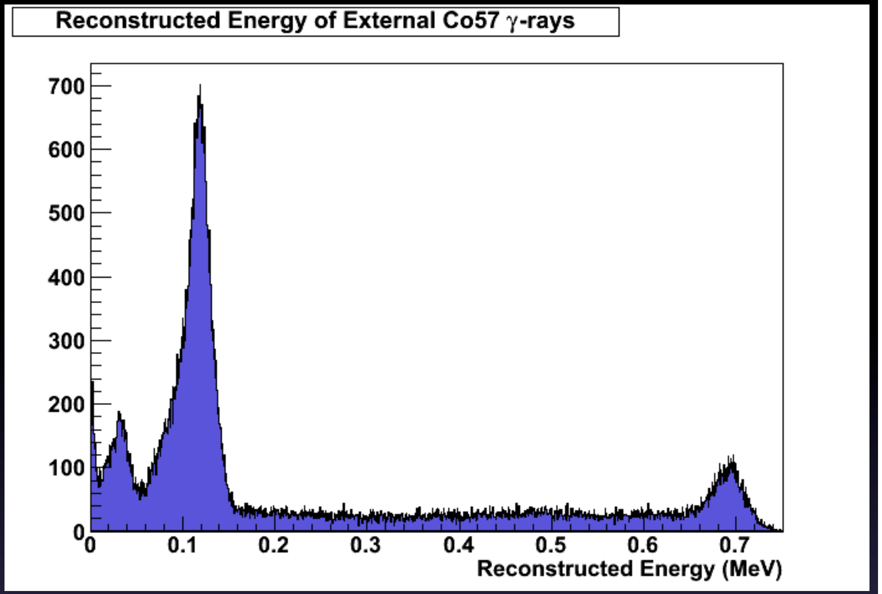
- Position resolution, bias studied using multiple distributions:
  - External gamma calibration sources, such as ^{57}Co
  - Here, ^{57}Co presents three peaks:
    - 692 keV photopeak
    - Overlapped 122 + 136 keV photopeaks
    - Overlapped 122 + 136 keV Compton edges near 40 keV
      - feature close to surface → excellent for radial leakage tests

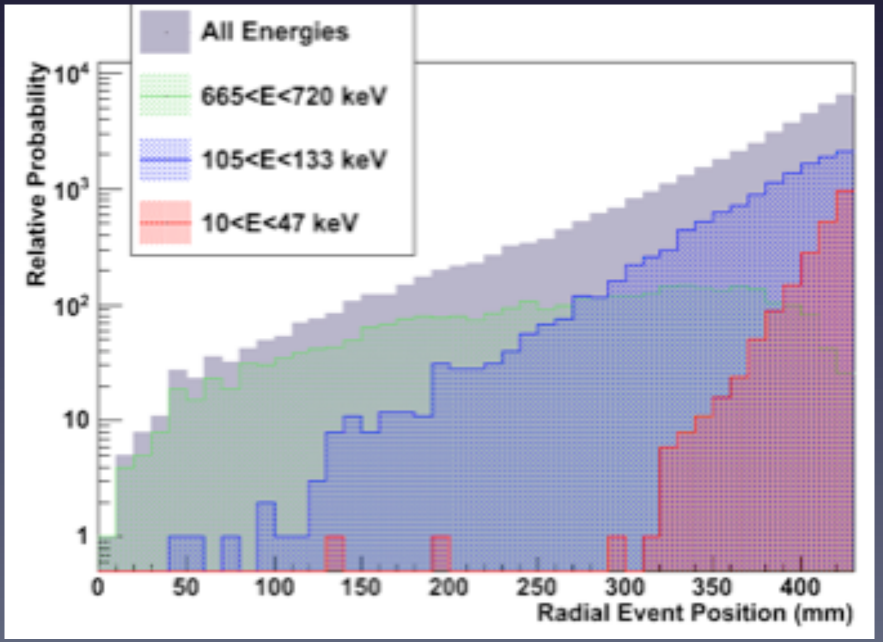




Position Reconstruction

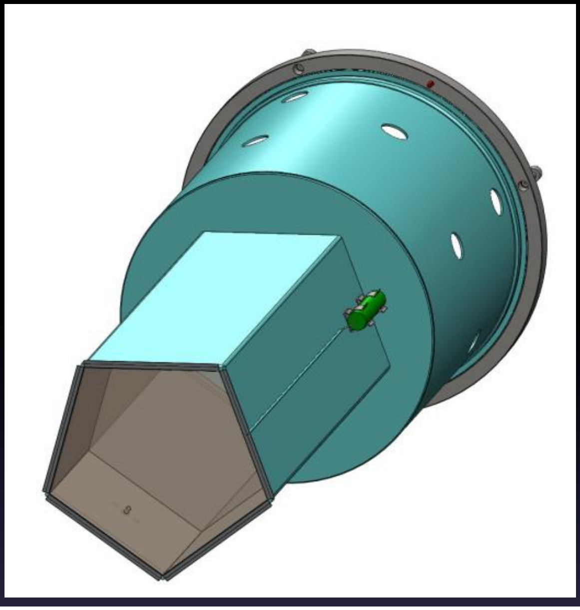
- Position resolution, bias studied using multiple distributions:
  - Also have U/Th gammas for “free” from PMTs
  - Combined rate ~ 100Hz

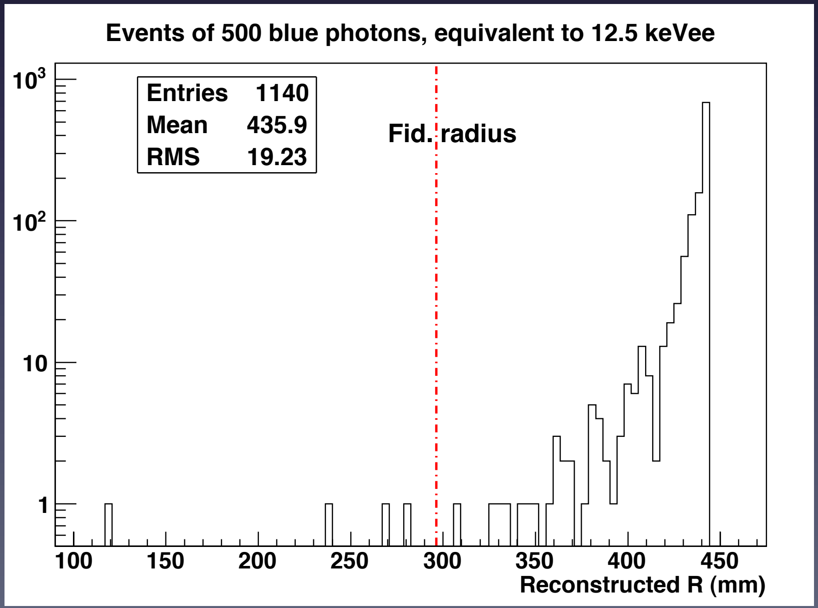




Position Reconstruction

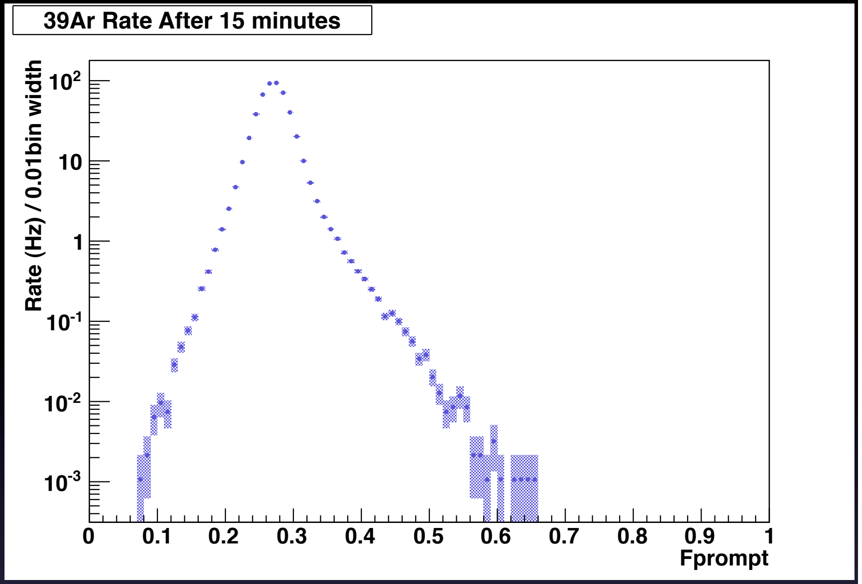
- Position resolution, bias studied using multiple distributions:
  - Visible light injecton: probe visible optics
  - UV light injection: probe UV + visible optics
  - Ability to benchmark and disentangle the visible and UV portions of our optical model

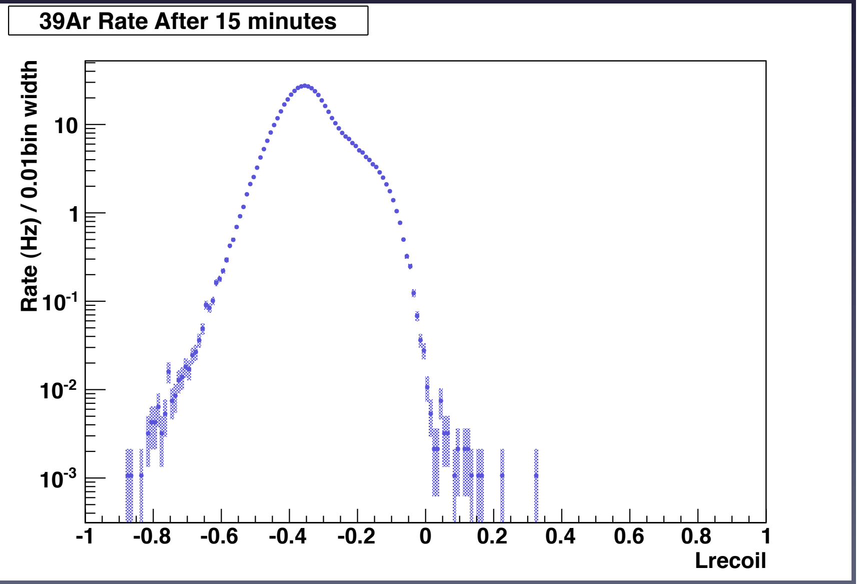




Pulse Shape Discrimination

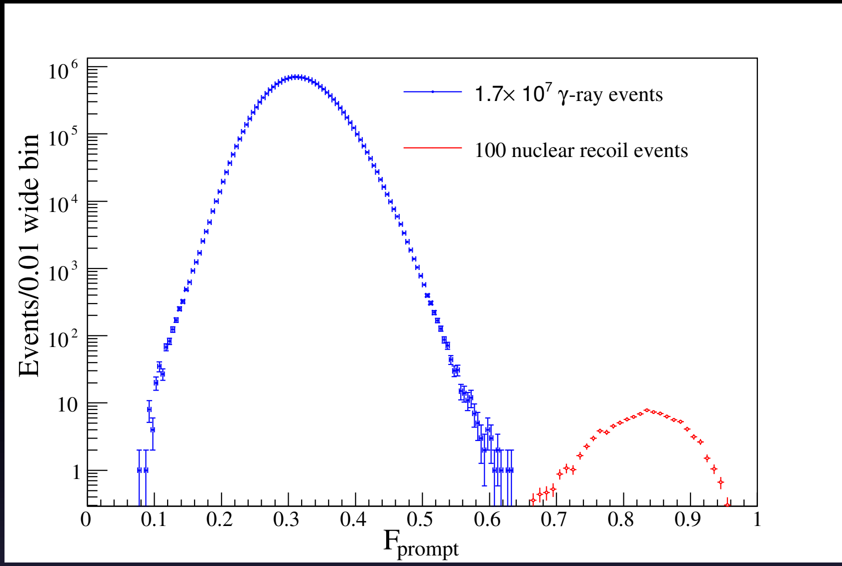
- Two approaches:
  - F_{prompt}~ total % of light detected in first 100ns of scintillation pulse
    - Uses integrated charge from waveforms
  - L_{recoil} = likelihood ratio that event is a nuclear recoil
    - Uses PE times from PE counter
    - Uses singlet and triplet ratios and lifetimes as input
    - Sensitive to non-standard events as well

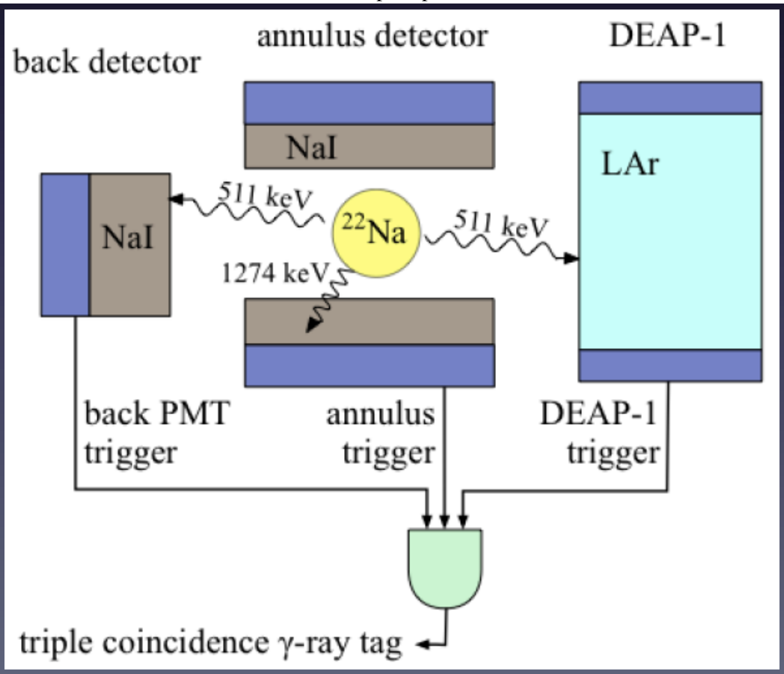




Pulse Shape Discrimination

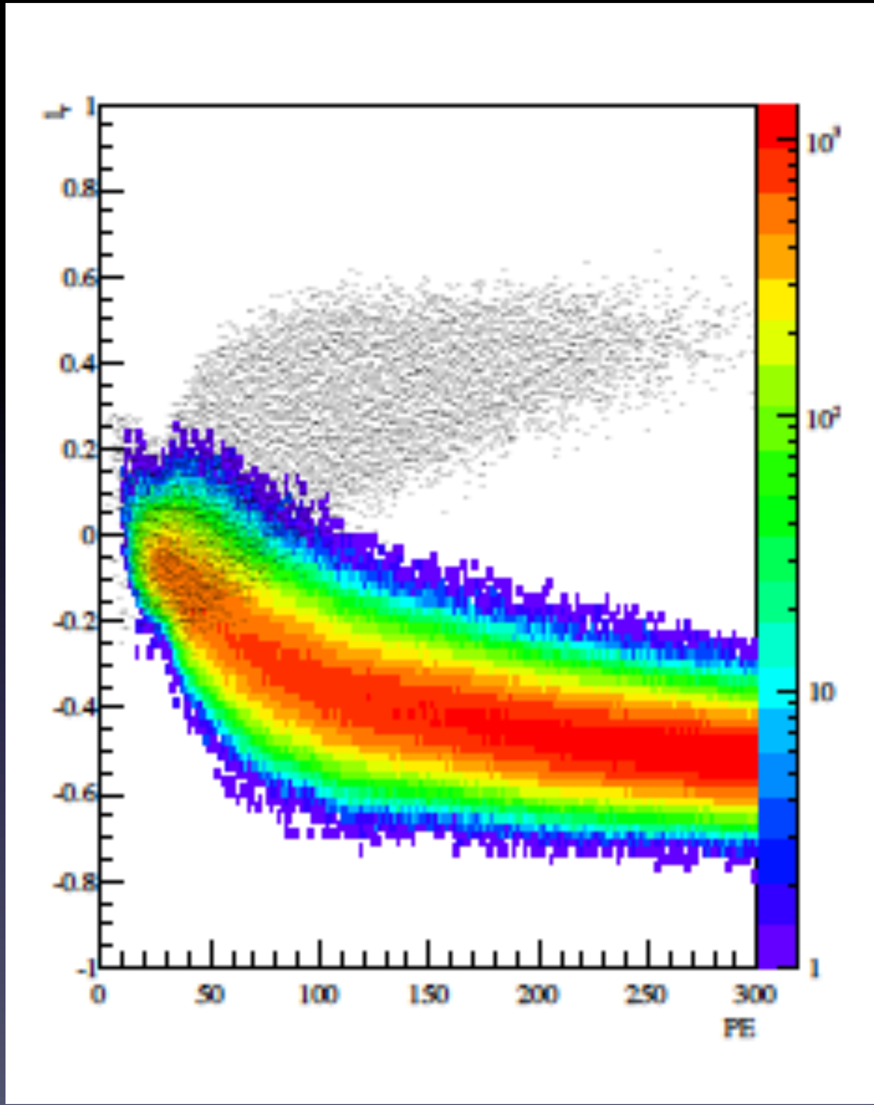
- F_{prompt}: established approach
  - DEAP-1 measurement with tagged gamma source has electron recoil leakage < 4.7 × 10^{-8} for 25keVee < E < 86keVee [M.G. Boulay, et al. arXiv:0904.2930]
  - Limited by light yield in DEAP-1, surface alphas, neutron "bank shots"
  - Plenty of room for improvement
- Fprompt breaks down at low observed energy/P.E. statistics…





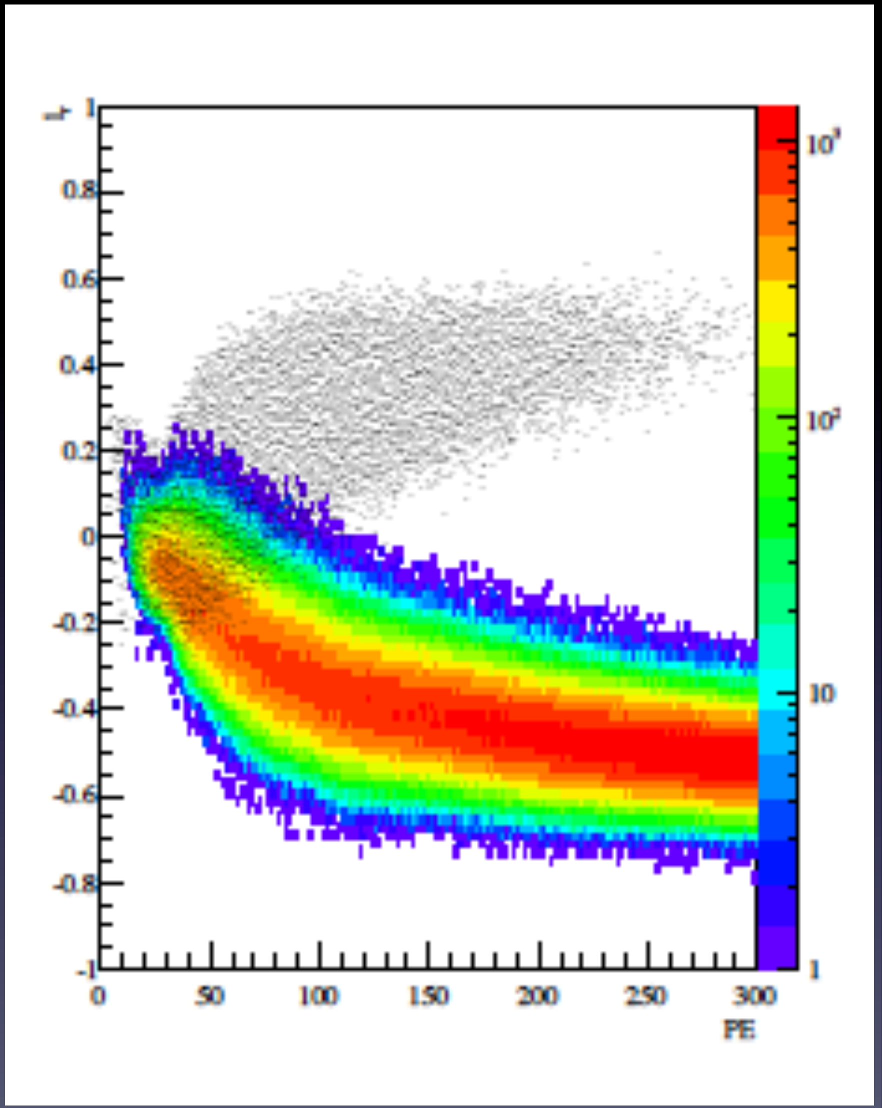
Pulse Shape Discrimination

- L_{recoil}: new approach
  - Exploits our new single PE counter
  - Similar approach can be used to reject certain classes of surface alpha events
  - Sensitive to small admixtures of electronic recoils in a nuclear recoil signal (e.g. gammas produced in inelastic neutron scatters)
  - Offers stronger rejection and extends to lower energies than F_{prompt}



Pulse Shape Discrimination

- PSD, using L_{recoil} or F_{prompt} , breaks down at low energies:
  - Low PE statistics
  - Differences in scintillation pulse shapes weaken at lower energies
- Breakdown's energy dependence will be very WIMP-like
- If events are due to ^{39}Ar decays (uniform) the spatial distribution in the detector will also be exactly WIMP like (uniform)
- <u>Any</u> large argon detector will have to prove WIMP candidates are not just due to electron recoil leakage



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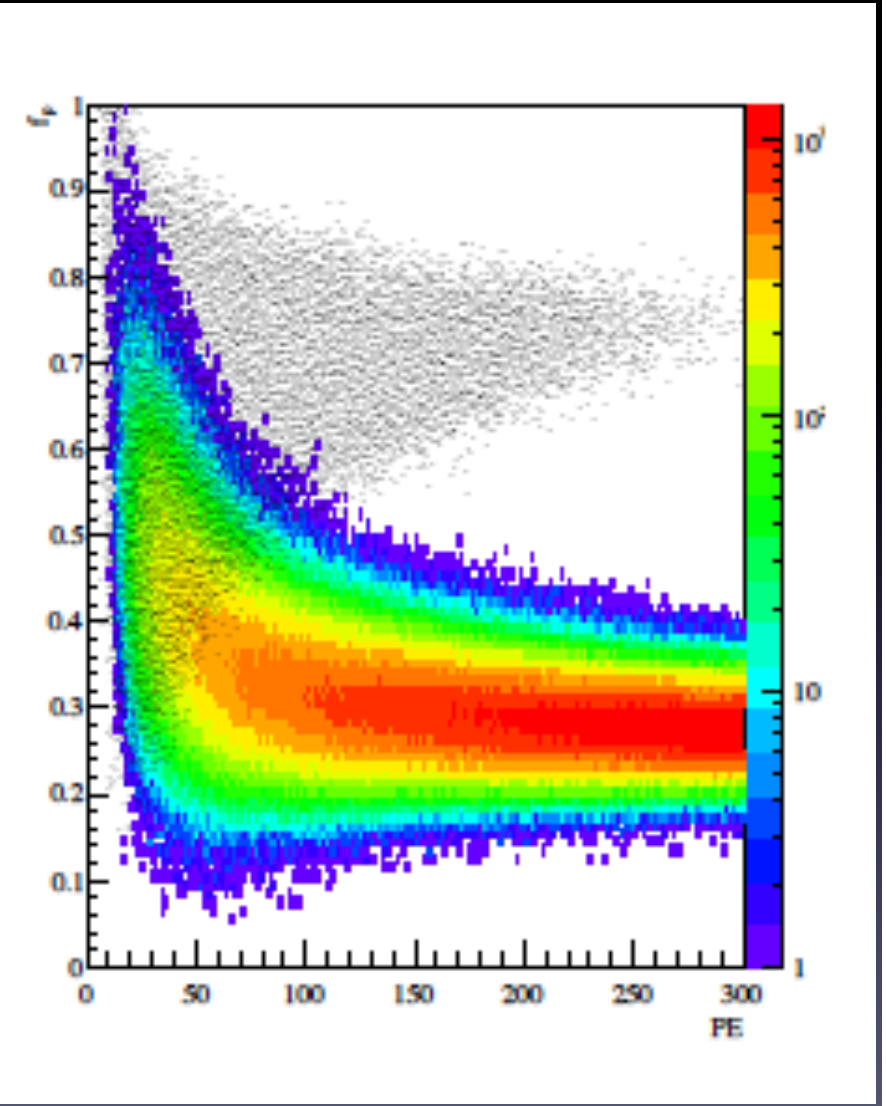

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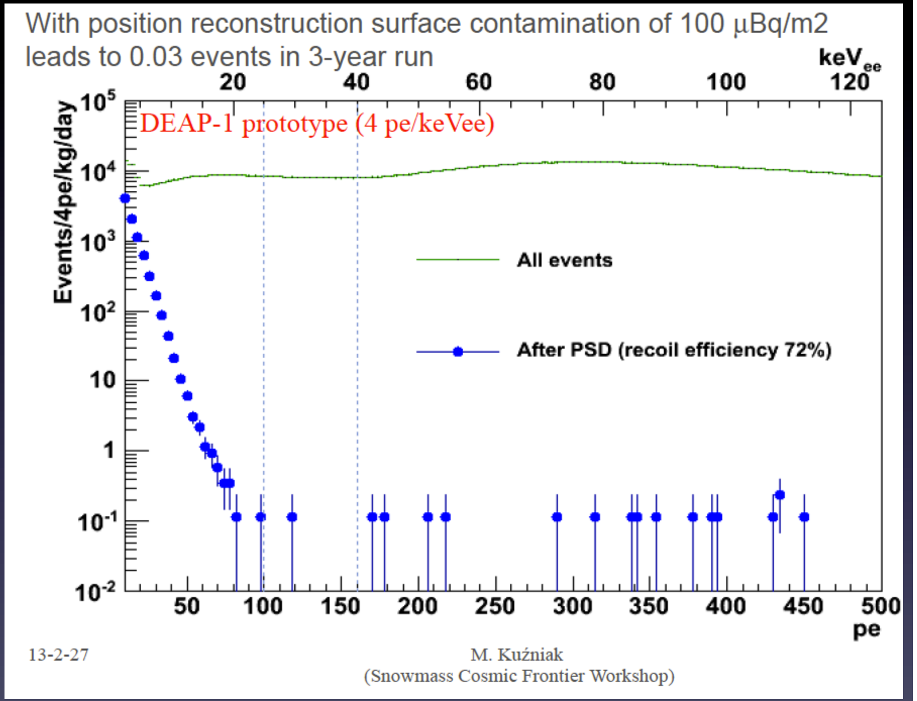
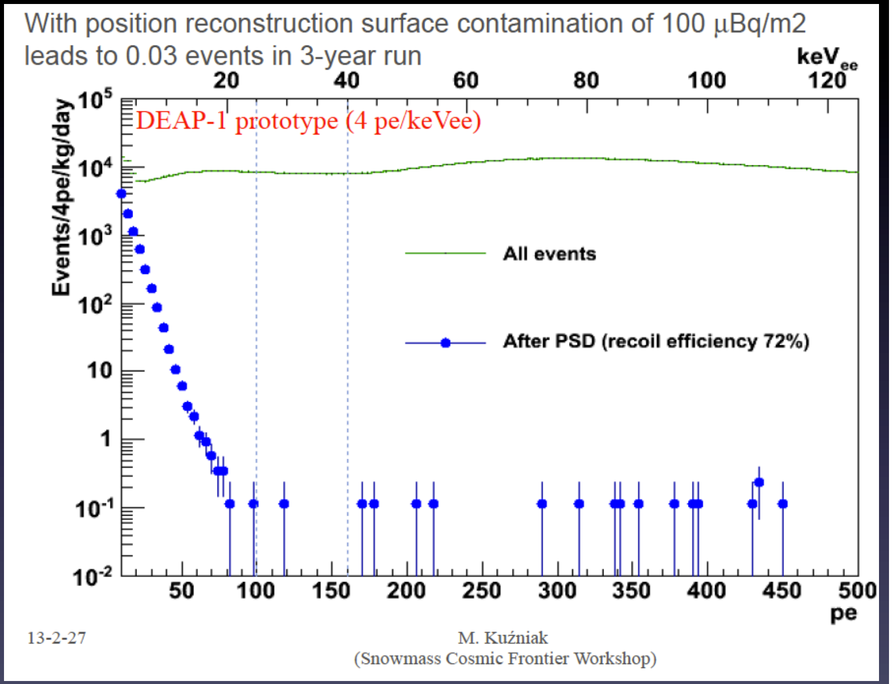


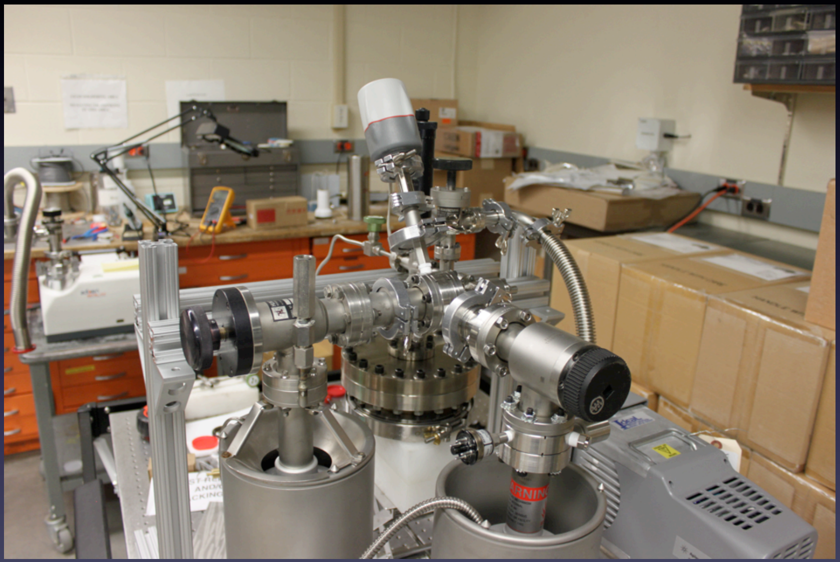
PSD Demonstration with Enriched Argon

- Our approach: make our radioactive detector MORE radioactive by spiking the argon target with additional levels of ^{39}Ar
- Natural argon run: establishes sum of all background rates
- Enriched argon run: Increase ^{39}Ar rate by ~8x (limited by DAQ)
- Difference in event rates between the two runs will yield pure ^{39}Ar decay PDF in MiniCLEAN
- Difference in event rates between the two runs AFTER PSD cuts are applied yields PSD leakage PDF convolved with 39Ar decay PDF
  - PSD leakage PDF for argon can be extracted @ MiniCLEAN's light yield (mapping between PE and energy)



The ^{39}Ar spike

- DOE isotope program has produced ^{39}Ar….as a byproduct
  - LANL program working to produce ^{26}Al, ^{32}Si
  - Production using irradiation of sealed KCl target
  - ^{39}Ar produced as a by-product: 138 MBq
  - ^{3}H also produced: 14 GBq
- We'll puncture the target to collect the gases present (including ^{39}Ar)
- LANL nuclear chemists will then cut open the target to extract the ^{26}Al, ^{32}Si

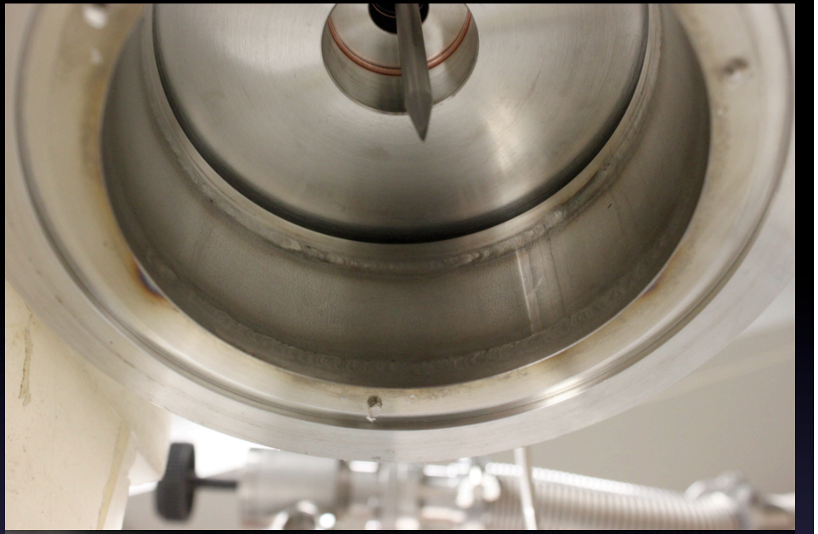


The ^{39}Ar spike

- Have constructed an extraction line to collect the 39Ar.
  - Enclose the target in a vacuum system
  - Puncture the target using a linear manipulator
  - Adsorb the gas using cold molecular sieve @ LN temps.

The ^{39}Ar spike

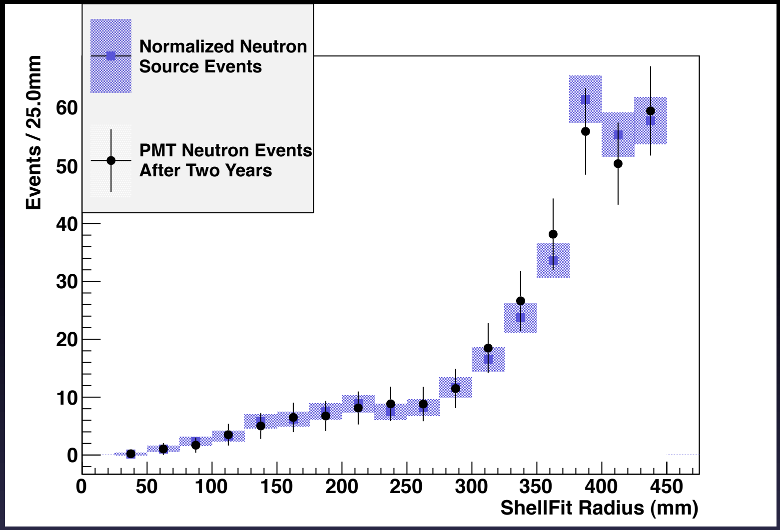
- Purify the sample:
  - Selective desorption by gradually warming the trap: argon will detach quickly
  - Expose to SAES getter to get ^{3}H, other impurities
  - End product: low pressure noble gases from target (He,Ne,Ar)
  - Only need ~24 kBq for MiniCLEAN

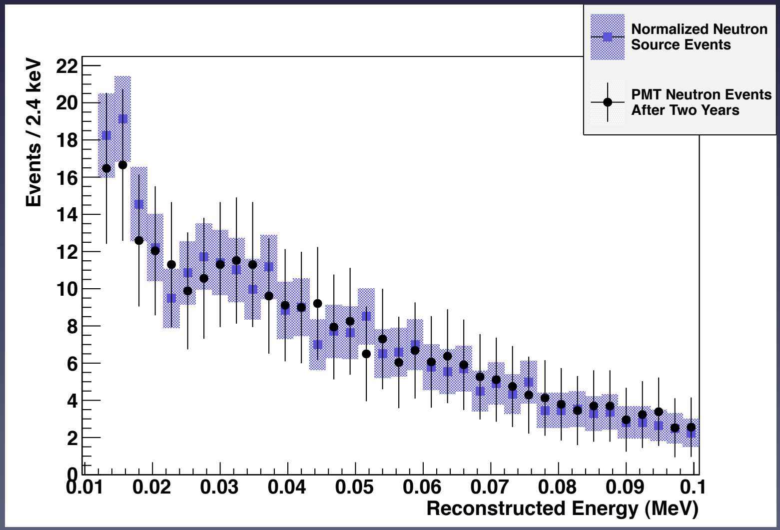


PMT Neutron Calibration

- Developing "Hot PMT" source:
  - U/Th in borosilicate glass, as with PMTs. But more.
- Deploy in calibration port
  - Difference introduced by propagation through IV steel→ MC predicts good extrapolation
- Possible to tag:
  - Look for de-excitation gammas from (α,n)
- Repeat with LNe target
  - Estimate change, if any, in background rate in going from LAr → LNe targets

Simulations of "Hot PMT" source and PMT Neutron Background





MiniCLEAN schedule

- – 4-5 weeks to condense argon gas into liquid argon
- – Begins in mid Dec.
- – 8 weeks of calibration and background running:
  - Energy scale
  - Position Reconstruction
  - Neutron calibration
  - Prelim PSD

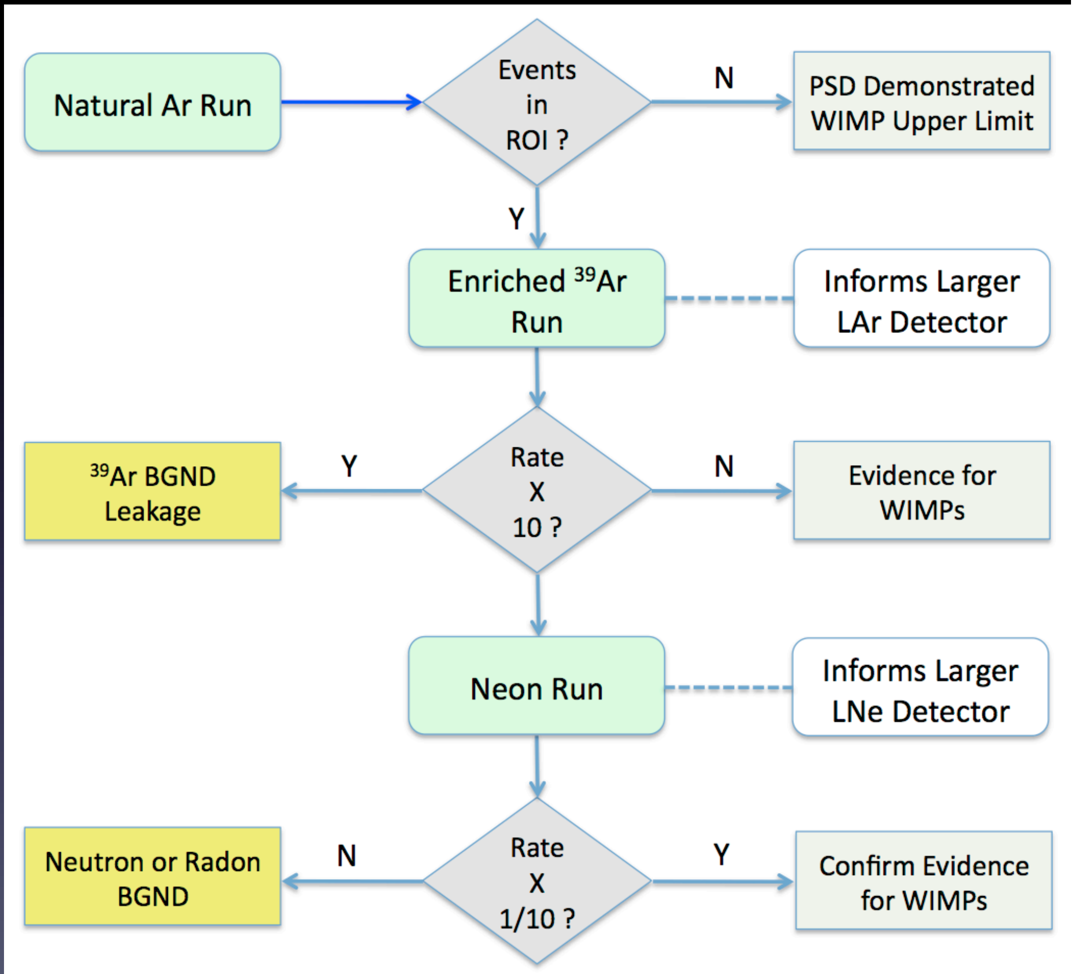
- Then > 100 days of enriched argon running
  - – Produce at least 10^{10} ^{39}Ar events in our fiducial volume

MiniCLEAN future

- After the spike, LAr phase is complete
  - Compare performance to DEAP-3600, DarkSide-50 when planning future of LAr DM experiments
- But…..we have a perfectly fine LNe capable detector underground ready to go…
  - Just need LNe and recovery system
  - Inform large LNe experiments for precision p-p solar neutrino measurement, WIMP searches, coherent neutrino-nucleus scattering experiments , etc…

Utility of LNe

- Running with two different ^{39}Ar rates, combined with a LNe run offers powerful test of any possible WIMP signal



Conclusion

- MiniCLEAN:
  - Will provide a stringent test of one unique approach to LAr-based WIMP searches:
    - Light yield of CLEAN scheme
    - Position reconstruction performance
  - Will yield a measurement of the limit of argon PSD to the 10^{10} rejection level
  - Move on to do all the above with LNe

Extra Slides

MiniCLEAN vs DEAP optics